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A 15-Year Plan for X-Ray Astronomy

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15-Year Plan for X-Ray Astronomy

1994-2008

Report of the

X-Ray Astronomy Program Working Group

June 1994

High Energy Astrophysics Branch, Astrophysics Division

Office of Space Science
National Aeronautics and Space Administration
Washington, D.C. 20546

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Foreword

The Office of Space Science (OSS) of the National Aeronautics and Space Administration (NASA) receives advice on scientific strategy and priorities from several external advisory bodies, principally the U.S. National Academy of Sciences. Academy guidance to the OSS Astrophysics Division is provided by dedicated panels, by *ad hoc* study groups, and, at 10-year intervals, by broadly mandated astronomy and astrophysics survey committees charged with making recommendations for the coming decade.

The two most recent Academy decade reviews are *The Decade of Discovery in Astronomy and Astrophysics* (the Bahcall Report, 1991) and *Astronomy and Astrophysics for the 1980s* (the Field Report, 1982). Both stress the importance of X-ray observations to the progress of astrophysics and outline the research initiatives that are needed. Because these conclusions reflect a consensus of the U.S. astronomical community, NASA recognizes an obligation to be responsive to the Academy recommendations. NASA retains the ultimate authority, however, to implement a program in X-ray astronomy in consultation with its own internal advisory groups.

In order to develop a long-range implementation plan for X-ray astronomy, the Astrophysics Division's High Energy Astrophysics Branch assembled an X-Ray Astronomy Program Working Group. The members were chosen for their expertise in X-ray astronomy and technology and for their knowledge of NASA flight and support programs in these areas. They were asked to examine not only the flight program, including both approved and potential future missions, but also the research and technology base, Mission Operations and Data Analysis (MO&DA), and advanced planning. Close liaison with the Academy's Bahcall Committee was maintained through the service of one Working Group member on the Committee itself and the service of eight members on the Committee's High Energy from Space panel.

The 15-year plan presented in this report incorporates the restructuring of the Advanced X-Ray Astrophysics Facility (AXAF) program, the reconfiguration of the X-Ray Timing Explorer (XTE), new opportunities for U.S. participation in international missions, and other recent program developments. The plan may thus be regarded as an up-to-date guide to the recommended program in X-ray astronomy through the opening years of the next century.

X-RAYS BLAZE FROM THE REMNANT OF TYCHO'S SUPERNOVA OF 1572 in this high-resolution image recorded by Germany's Roentgen Satellite (ROSAT) in 1991. Detailed ROSAT imaging, combined with X-ray spectroscopy by Japan's Advanced Satellite for Cosmology and Astrophysics (ASCA), are yielding new insights into the composition and evolution of supernova remnants.

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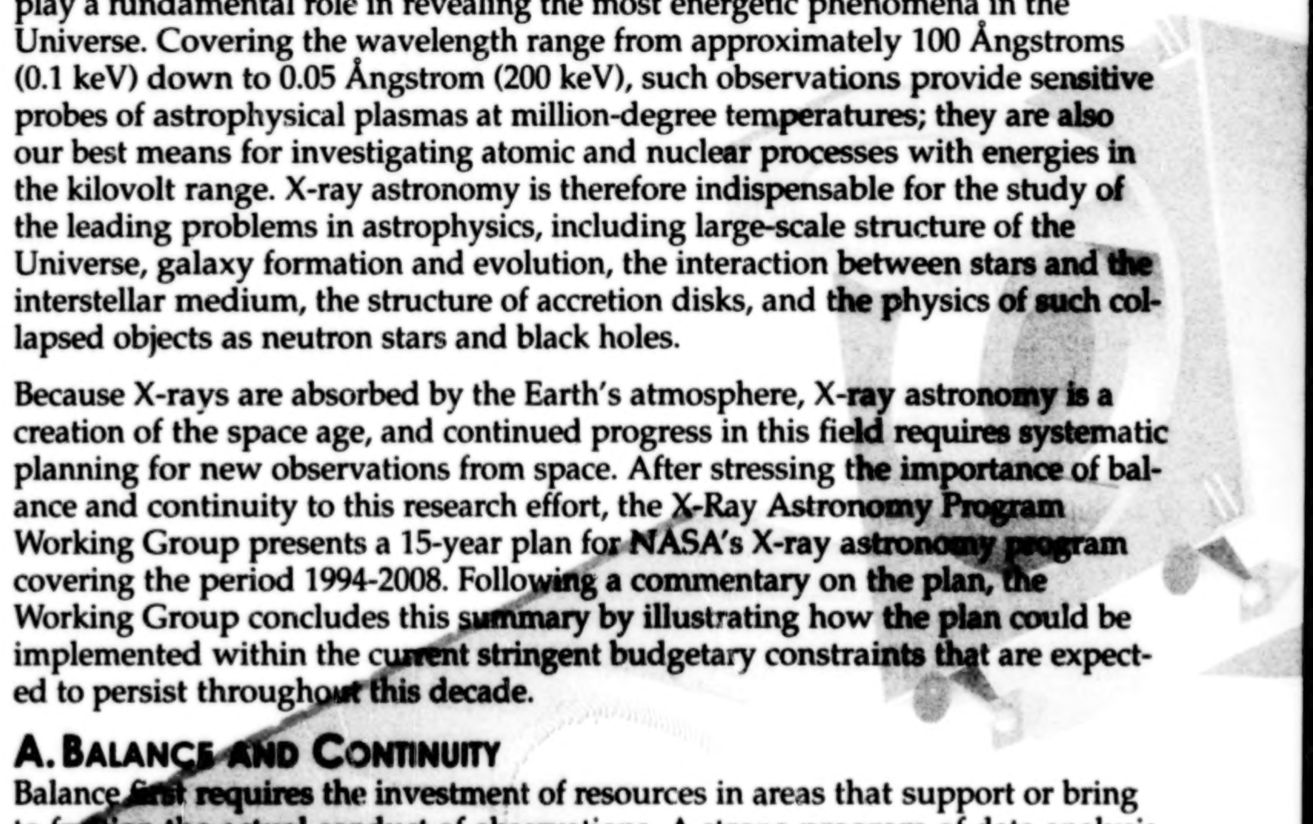
Executive Summary

Celestial X-ray astronomy began in 1962 with the first detection of an X-ray source more distant than the Sun (Scorpius X-1) with a rocket-borne instrument. In only three decades, X-ray astronomy has grown from infancy to maturity, gaining parity with observations in other spectral regions at the forefront of astrophysical research.

The reason for this growth is both simple and compelling: X-ray observations play a fundamental role in revealing the most energetic phenomena in the Universe. Covering the wavelength range from approximately 100 Ångstroms (0.1 keV) down to 0.05 Ångstrom (200 keV), such observations provide sensitive probes of astrophysical plasmas at million-degree temperatures; they are also our best means for investigating atomic and nuclear processes with energies in the kilovolt range. X-ray astronomy is therefore indispensable for the study of the leading problems in astrophysics, including large-scale structure of the Universe, galaxy formation and evolution, the interaction between stars and the interstellar medium, the structure of accretion disks, and the physics of such collapsed objects as neutron stars and black holes.

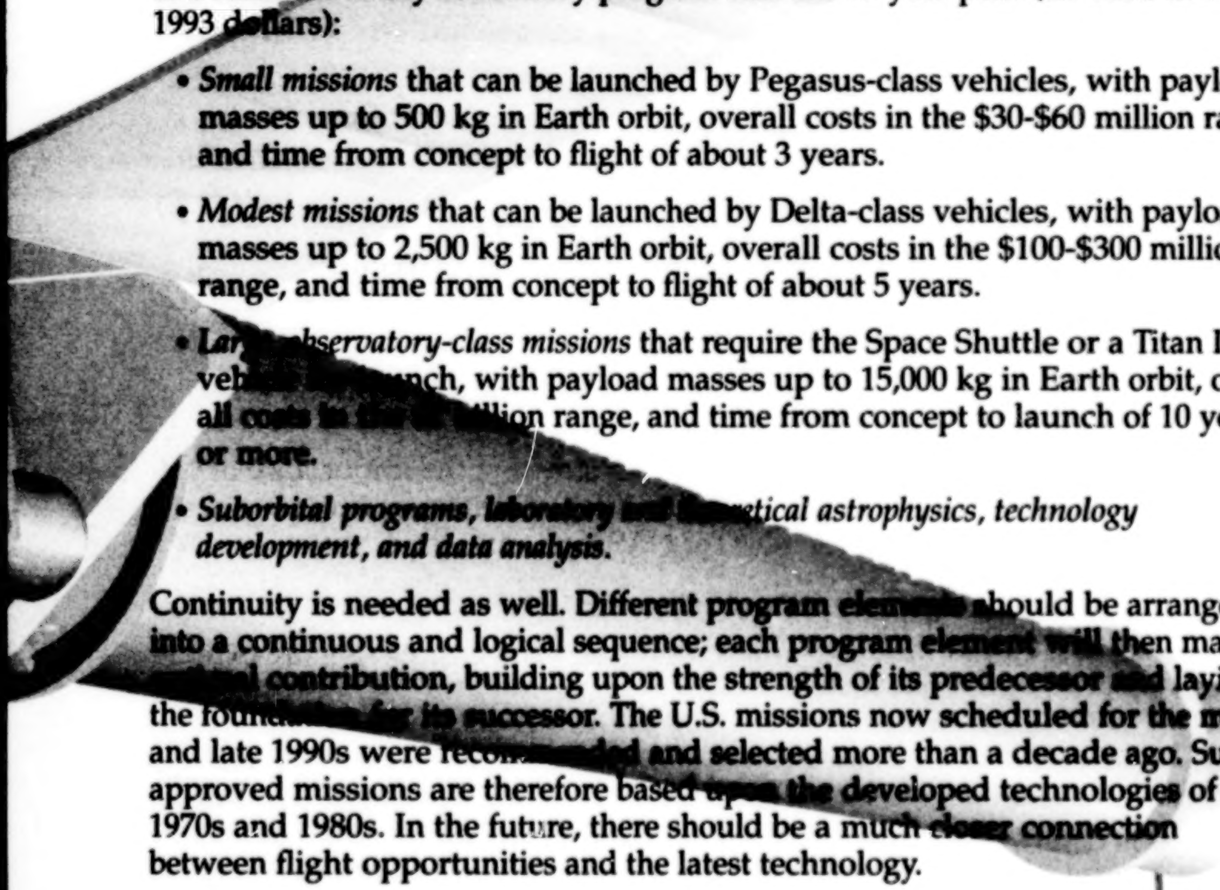


Because X-rays are absorbed by the Earth's atmosphere, X-ray astronomy is a creation of the space age, and continued progress in this field requires systematic planning for new observations from space. After stressing the importance of balance and continuity to this research effort, the X-Ray Astronomy Program Working Group presents a 15-year plan for NASA's X-ray astronomy program covering the period 1994-2008. Following a commentary on the plan, the Working Group concludes this summary by illustrating how the plan could be implemented within the current stringent budgetary constraints that are expected to persist throughout this decade.

A. BALANCE AND CONTINUITY

Balance first requires the investment of resources in areas that support or bring to fruition the actual conduct of observations. A strong program of data analysis and interpretation, supported by Mission Operations and Data Analysis (MO&DA) funding, is necessary for the transformation of data into useful knowledge. Also important is the development of new technology, which is absolutely essential for the advancement of astrophysical research. To ensure the future of X-ray astronomy, NASA must maintain an appropriate level of support for technology development.

Balance is also needed in NASA's flight program. Past experience has demonstrated the benefits of a broad range of observational approaches to astrophysical research, ranging from rocket and balloon flights, through small and moderate-class satellites, to major observatories in orbit. A balanced research effort requires a diversity of observing platforms together with recurring, regular flight opportunities. The Working Group has therefore incorporated four components of a balanced X-ray astronomy program into the 15-year plan (all costs in FY 1993 dollars):



- *Small missions* that can be launched by Pegasus-class vehicles, with payload masses up to 500 kg in Earth orbit, overall costs in the $30-$60 million range, and time from concept to flight of about 3 years.
- *Modest missions* that can be launched by Delta-class vehicles, with payload masses up to 2,500 kg in Earth orbit, overall costs in the $100-$300 million range, and time from concept to flight of about 5 years.
- *Large observatory-class missions* that require the Space Shuttle or a Titan IV vehicle for launch, with payload masses up to 15,000 kg in Earth orbit, overall costs in the [illegible] range, and time from concept to launch of 10 years or more.
- *Suborbital programs, laboratory and theoretical astrophysics, technology development, and data analysis.*

Continuity is needed as well. Different program elements should be arranged into a continuous and logical sequence; each program element will then make an natural contribution, building upon the strength of its predecessor and laying the foundation for its successor. The U.S. missions now scheduled for the middle and late 1990s were recommended and selected more than a decade ago. Such approved missions are therefore based upon the developed technologies of the 1970s and 1980s. In the future, there should be a much closer connection between flight opportunities and the latest technology.

The 15-year plan for X-ray astronomy presented below is rational, affordable, and responsive to the needs for programmatic balance and continuity. The High Energy Astrophysics Branch of NASA's Astrophysics Division should seek to implement those programs that most directly and effectively support the plan.

B. 15-YEAR PLAN FOR X-RAY ASTRONOMY: 1994-2008

Complete and Launch the Advanced X-Ray Astrophysics Facility (AXAF):

- Launch AXAF-I (Imaging) in 1998.
- Negotiate flight of the X-Ray Spectrometer (XRS) aboard Japan's ASTRO-E mission in 1999.

Begin an X-Ray "Observer" Mission Series:

Phase in experiments in the Delta launch-vehicle class to complement AXAF and Explorer-class missions and maintain program balance. Candidates include:

- High-energy imaging between 20 and 200 keV;
- Very-high-resolution spectroscopy;
- Grazing-incidence imaging up to 40 keV;
- High-throughput spectroscopy; and
- An all-sky survey from 2 to 10 keV.

Participate Actively in the Explorer Program:

- Launch the X-Ray Timing Explorer (XTE) in 1995 and operate it for as long as it remains scientifically productive.
- Propose new X-ray experiments in the University Explorer (UNEX), Small Explorer (SMEX), and Middle-Range Explorer (MIDEX) mission classes for a variety of investigations. Candidates include a deep, wide-field survey from 0.1 to 2 keV; an all-sky spectroscopic survey of the soft X-ray diffuse background; all-sky temporal monitoring; and nebular spectroscopy.

Strengthen the Research and Technology Base:

- Identify, define, and demonstrate forefront X-ray technology through NASA's AstroTech 21 initiative.
- Augment funding for X-ray detector development, X-ray optics, and theoretical and laboratory astrophysics.
- Continue an active program of high-altitude balloon and sounding-rocket flights.

Ensure Support for Mission Operations and Data Analysis:

- Continue vigorous Guest Observer programs for current and future missions.
- Maintain support for mission science centers.
- Ensure support for archival data analysis and access through the Astrophysics Data Program, the Long-Term Space Astrophysics program, the Astrophysics Theory Program, and the Astrophysics Data System.

Continue U.S. Participation in International Missions:

Build upon successes of the operational Roentgen Satellite (ROSAT) and Advanced Satellite for Cosmology and Astrophysics (ASCA) missions through continued U.S. participation in future international X-ray experiments:

- Satelite de Aplicaciones Cientificas-B (SAC-B), Argentina/USA (1995).
- Spectrum X-Gamma, Russia/Denmark/USA (1995).
- X-Ray Multimirror Mission (XMM), ESA/USA (1998).
- ASTRO-E, Japan/USA (proposed, 1999).

Begin Planning for X-Ray Missions Early in the 21st Century:

- Define the role of a new observatory-class mission in light of emerging scientific and technological opportunities.

C. Commentary on the Plan

This plan achieves balance by incorporating all program components listed earlier. In the area of flight programs, it includes small missions (e.g., Explorers), modest missions (e.g., the X-ray "Observers"), and large, observatory-class missions (AXAF and its 21st-century successor). The plan also includes suborbital research, laboratory and theoretical astrophysics, technology development, and data analysis. U.S. participation in international missions will take various forms and may involve activities in all of these program components.

- **Complete and launch AXAF.**
- **Begin an X-ray "Observer" mission series.**
- **Participate actively in the Explorer program.**
- **Strengthen the research and technology base.**
- **Ensure support for Mission Operations and Data Analysis.**
- **Continue U.S. participation in international missions.**
- **Begin planning for X-ray missions early in the 21st century.**

C.1. Complete and launch AXAF.

AXAF-I (Imaging) will carry out high-resolution imaging and dispersive spectroscopy; the X-Ray Spectrometer (XRS), originally intended for AXAF and later for AXAF-S (Spectroscopy), is designed for high-resolution nondispersive spectroscopy. Covering the energy band from 0.1 to 10 keV, AXAF will address major questions in virtually every area of Galactic and extragalactic astronomy.

Using the imaging capability of AXAF-I (Figure 1), we will be able to resolve, for example, discrete components of the cosmic X-ray background radiation; this mission will also survey large-scale structure in the Universe, pinpoint active galactic nuclei (AGN), determine the location of X-ray binaries throughout the

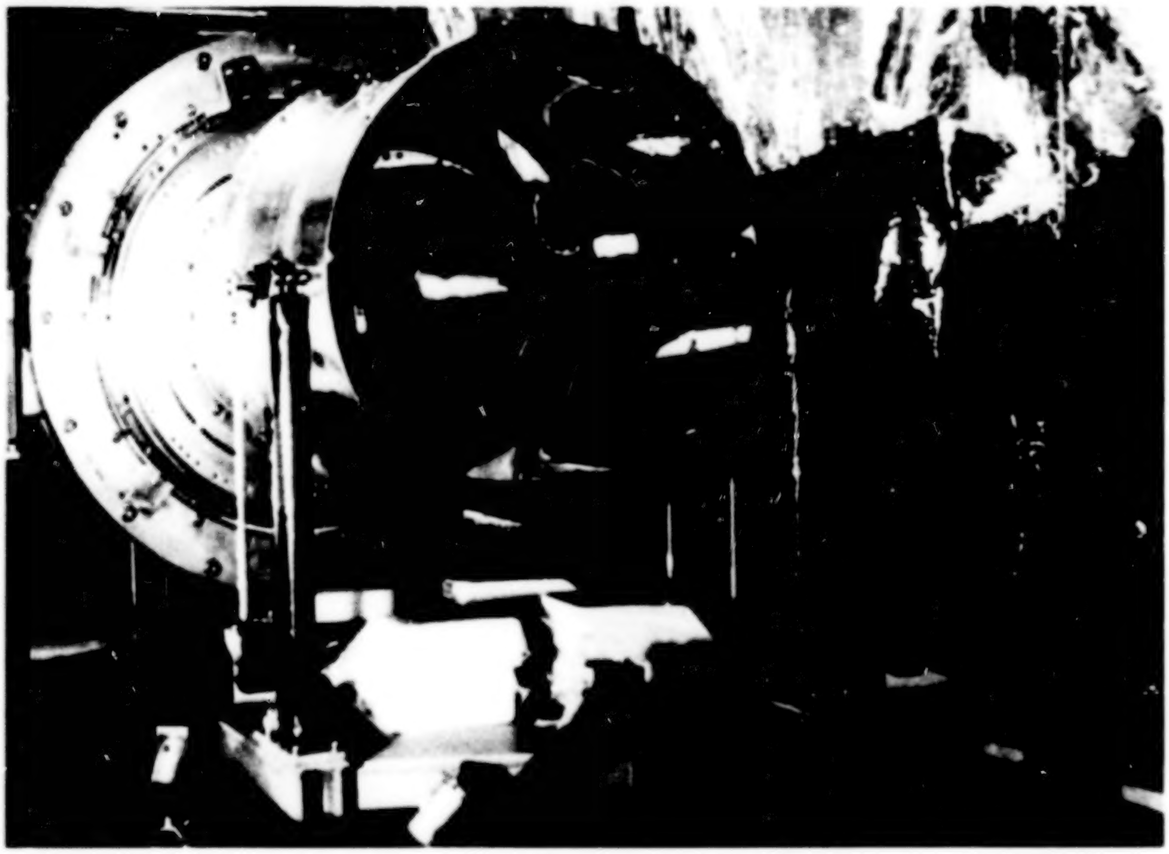


Figure 1. THE FIRST AND LARGEST AXAF-I MIRROR PAIR passes its focusing test with flying colors at NASA's Marshall Space Flight Center in 1992. The pair yields an angular resolution of 0.23 arcsecond—an unprecedented achievement in the figuring of large X-ray primary mirrors.

Local Group of galaxies, and probe early stellar evolution in starburst galaxies. AXAF-I spatially resolved spectroscopy will help us map the hot gas and dark matter in galaxies and clusters of galaxies and measure the Hubble constant via the Sunyaev-Zel'dovich effect. The AXAF spectrometers will examine the structure and energetics of stellar coronae and explore nucleosynthesis through studies of the chemical composition of supernova ejecta. The AXAF project includes participation from Germany, the Netherlands, and the United Kingdom.

C.2. Begin an X-Ray "Observer" mission series.

Many X-ray observations do not demand an observatory in the AXAF class, but do require greater capabilities than can be provided by Explorers. The Working

Group has given the name "Observers" to these new missions, which would be launched by Delta-class expendable vehicles; costs would lie in the range $100 to $300 million FY 1993 dollars, with development times of 5 years or so. The X-ray "Observers" would be phased into the program to carry out a variety of important investigations, including the following (this list carries no implication of priority):

- *High-energy imaging from 20 to 200 keV.* Configured with sufficient effective area and angular resolution, this mission would provide the sensitivity needed to study representative samples of objects instead of only the brightest members of a class. Scientific objectives include studies of the high-energy spectra of X-ray binaries and active galactic nuclei, as well as cyclotron features in pulsars.
- *Very-high-resolution spectroscopy.* A spectrograph with an energy resolution of 30,000 or so would permit the fine structure of atomic X-ray lines to be resolved and the line shapes measured; details of the physics of all classes of X-ray sources could then be studied. The attainment of very high resolving power (e.g., with gratings and grazing-incidence optics) will require innovations in fabrication and structures.
- *Grazing-incidence imaging up to 40 keV.* Imaging in this energy region would permit high-sensitivity observations in the portion of the X-ray spectrum in which nonthermal emission mechanisms begin to dominate thermal processes. Even moderate angular resolution would yield a signal-to-noise ratio sufficient for detailed spectroscopic studies of large samples of active galactic nuclei and X-ray binaries. Identifying efficient X-ray reflectors at these energies will be required, as well as improving high-energy imaging detectors.
- *High-throughput spectroscopy.* A mission analogous to the Large Area Modular Array of Reflectors (LAMAR), studied during the 1980s for possible Space Shuttle flight and Space Station deployment, could carry out detailed, broadband spectroscopy of faint sources and time-resolved spectroscopy of bright sources. The need for a high-throughput mission of this type has been noted in many previous studies.
- *An all-sky survey from 2 to 10 keV.* Now that ROSAT has completed a sensitive survey at lower energy (Figure 2), we should obtain a corresponding arcminute view of the X-ray sky from 2 to 10 keV. The telescope could also be used in a pointed mode to make more sensitive observations of selected sources. All classes of X-ray emitters would be studied.

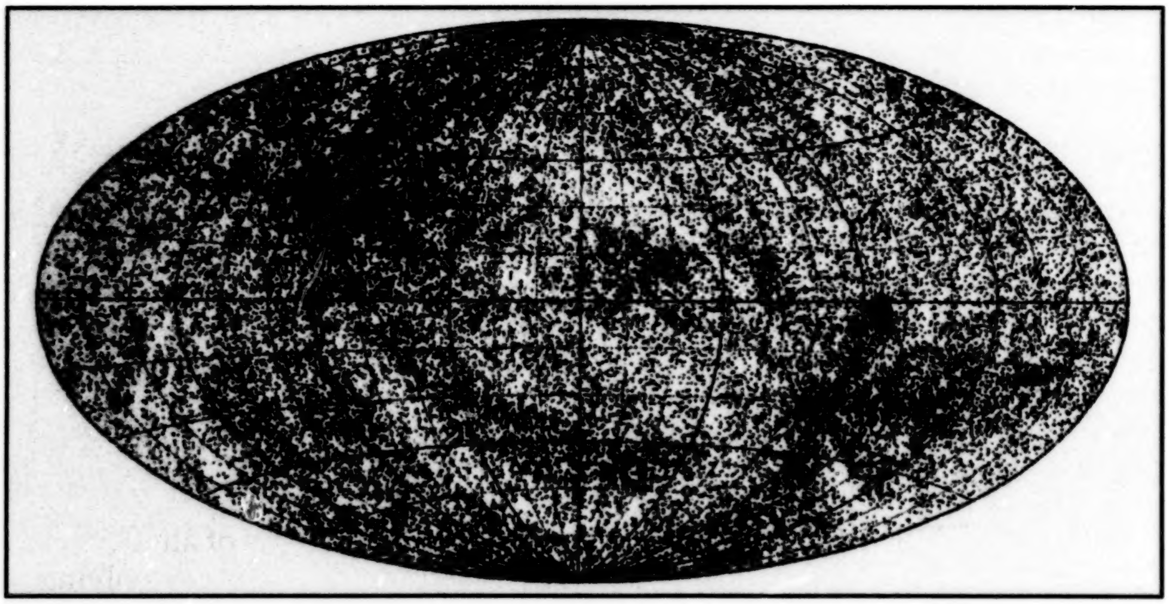


Figure 2. ROSAT ALL-SKY MAP OF X-RAY SOURCES was compiled from observations in the energy range from 0.1 to 2 keV. A corresponding arcminute view of the X-ray sky from 2 to 10 keV should be obtained early in the next century through the flight of a new X-ray "Observer" moderate-class satellite.

C.3. Participate actively in the Explorer program.

The X-Ray Timing Explorer (XTE) will make new observations of rapid X-ray variability near collapsed objects (e.g., white dwarfs, neutron stars, and black holes), thereby providing a probe of ultradense matter, ultrahigh magnetic fields, the structure of accretion disks, and the nonthermal properties of active galactic nuclei. However, XTE is the only X-ray Explorer mission to be approved since NASA's third Small Astronomy Satellite (SAS-3), which operated from 1975 until 1979. The Working Group therefore hopes that the 1991 restructuring of the Explorer program into the UNEX, SMEX, and MIDEX mission classes will provide more frequent flight opportunities for modest experiments; these will cost from \$30 to \$60 million in FY 1993 dollars and require 3 years or so to develop.

In particular, the Working Group notes the promise of the restructured Explorer program for carrying out such X-ray investigations as the following: (a) a deep, wide-field (100 deg^2) survey from 0.1 to 2 keV, to study X-ray counterparts of optical sources and search for distant clusters of galaxies; (b) an all-sky spectroscopic survey of the soft X-ray diffuse background, to map this radiation at high spectral resolution and elucidate the role of hot gas in the interstellar medium;

(c) all-sky temporal monitoring, to study bright X-ray sources and detect transients; and (d) nebular spectroscopy, to study extended objects and the interstellar medium at high spectral resolution.

C.4. Strengthen the research and technology base.

NASA's Research and Analysis (R&A) program includes Supporting Research and Technology (SR&T) funding for basic technology development, laboratory astrophysics and suborbital research from sounding rockets and high-altitude balloons. Over the past decade, however, there has been virtually no real growth in SR&T funding, even though needs in laboratory astrophysics and some other areas have expanded. The Working Group strongly recommends an augmentation in SR&T funding for X-ray detector development, X-ray optics, and laboratory and theoretical astrophysics.

Support is also critical for investigations that require the most challenging technology permitted by the state of the art. These typically demand high initial investments and thus lie beyond the capabilities of most university-based research groups. Examples include large structures, advanced optics, long-lived cryogenic systems, and microelectronics fabrication—forefront technology that could redirect the course of X-ray astronomy in the next century (Figure 3). The R&A Advanced Technology Development (ATD) program provides such support to specific planned or approved missions whose technology needs have already been defined.

Another channel for the support of forefront technology is the AstroTech 21 program—jointly sponsored by NASA's Office of Space Science (OSS) and Office of Advanced Concepts and Technology (OACT)—which encourages collaborations among government, industry, and universities. The Working Group urges the strengthening of AstroTech 21 to permit identification, definition, and demonstration of forefront technology applicable to X-ray astronomy, particularly in the areas of optics and sensors.

The suborbital program offers opportunities for rapid instrument deployment, high-risk exploratory investigations, and the training of young investigators. High-altitude balloons, which can now remain aloft for two weeks or more, also provide important avenues for hard X-ray observations. As the study of Supernova 1987A showed, both rockets and balloons permit quick responses to transient phenomena and may offer capabilities that cannot be matched by spacecraft already in orbit. The Working Group therefore urges continuation of an active NASA suborbital program of sounding-rocket and high-altitude balloon flights.

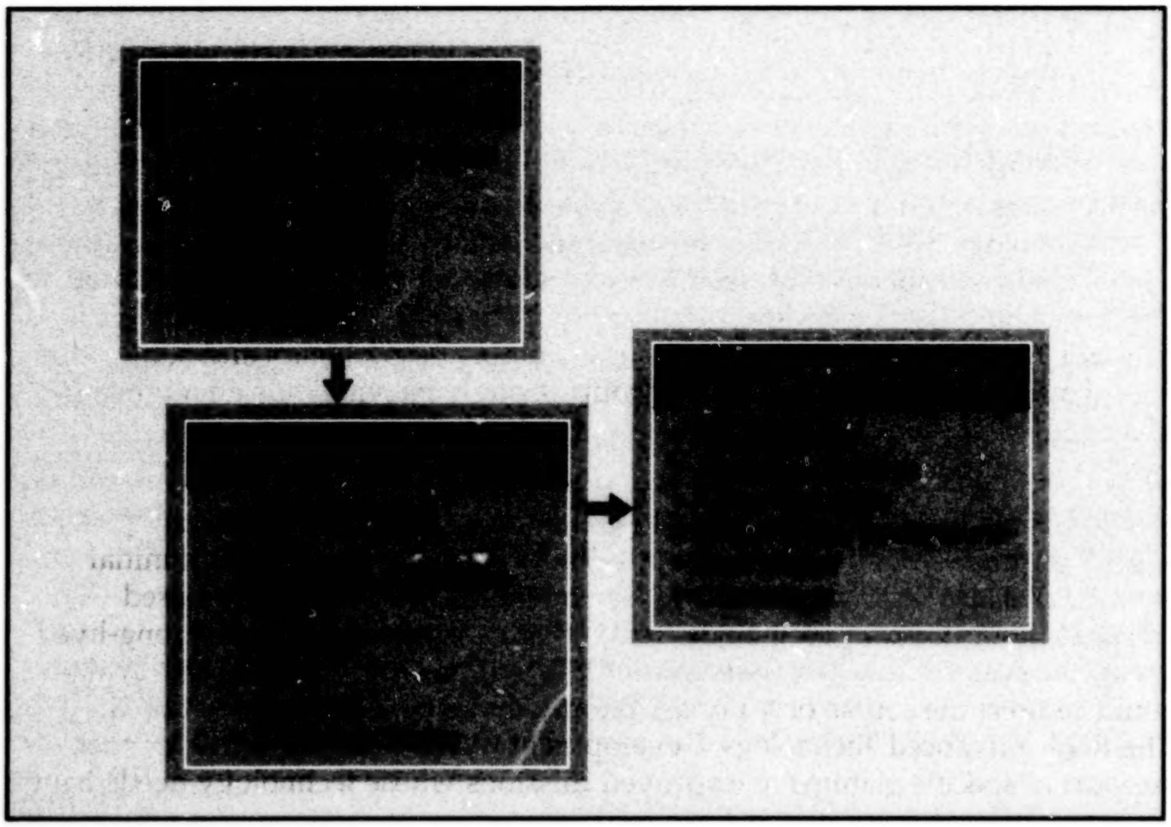


Figure 3. ADVANCED TECHNOLOGY HOLDS THE KEY to the new X-ray missions and astrophysical knowledge of the future.

C.5. Ensure support for Mission Operations and Data Analysis.

The scientific return from X-ray astronomy missions is not realized until the data have been analyzed, interpreted, and transformed into new contributions to knowledge. Although modest SR&T funding is available to support theoretical studies of high-energy astrophysical processes and modeling, the great bulk of X-ray data analysis is supported through the Mission Operations and Data Analysis (MO&DA) program. In view of mounting budgetary pressures to scale back MO&DA support—including proposals to terminate active missions while they are still producing important scientific results—the Working Group is especially concerned that a healthy level of support for data analysis be maintained. A balanced program must provide for the analysis of results from current and past missions, as well as the provision of new flight opportunities.

Guest Observer (GO) programs, which reach a broad spectrum of the scientific community, are needed to optimize X-ray observing programs. The Working Group strongly endorses the continuation of vigorous GO programs for both current and future NASA missions, including XTE and AXAF, and for international missions involving U.S. participation.

Mission science centers play key roles in serving users and in consolidating and disseminating mission data. Support should be maintained for current mission science centers and for those planned for XTE and AXAF. The High Energy Astrophysics Science Archive Research Center (HEASARC) at NASA's Goddard Space Flight Center should continue to consolidate X-ray data from past missions as their individual science centers are phased out.

Fruitful analysis and interpretation of archival data continues long after mission-specific programs have been completed. Most of this critically important work is supported by MO&DA grants to the scientific community from the Astrophysics Data Program (ADP), the Long-Term Space Astrophysics (LTSA) program, and the Astrophysics Theory Program (ATP). The Working Group recommends that these highly productive MO&DA grant programs be extended to include the data from new missions as they become publicly available. A policy that would gradually move mission-specific data-analysis support from GO grants into ADP, LTSA, and ATP grants would provide a mechanism for keeping the latter programs healthy and vigorous. The Astrophysics Data System (ADS), designed to promote ready access to archival data, remains an important component of the MO&DA program.

The Working Group views support for all of these MO&DA functions as essential to optimize the scientific return from flight missions and to achieve the widest possible data dissemination.

C.6. Continue U.S. participation in international missions.

International X-ray missions provide low-cost, low-risk access to space for many U.S. investigators. Vigorous U.S. involvement in such missions is an important element of a balanced X-ray astronomy program. Current cooperation on the German ROSAT and the Japanese ASCA missions provides an example of the benefits. Similar U.S. access to X-ray data in return for program contributions has been obtained for SAC-B, Spectrum X-Gamma, and XMM, and is being negotiated for ASTRO-E. The flight of U.S. X-ray instruments on Germany's Shuttle-deployed AstroSPAS platform (a "SpectroSPAS" mission) should also be pursued. The Working Group endorses exploiting such opportunities for U.S. scientific participation in international missions and urges that adequate funding continue to be made available without impacting the Explorer program or Research and Analysis activities.

C.7. Begin planning for X-ray missions early in the 21st century.

Advanced planning should begin now for an observatory-class mission to succeed AXAF in the next century. This task will demand development of enabling technologies for optics, instrumentation, structures, launch, and deployment. Detailed mission characteristics should be determined by the scientific and technological opportunities that will emerge during the remainder of this decade. However, it is already clear that such an advanced observatory should provide for imaging and spectroscopy at very high resolution, which implies the need for high throughput (a collecting area of at least 1 m^2) combined with the best achievable spatial resolution (goal of approximately 1 arcsecond) for a mission of that scope.

D. IMPLEMENTATION

In Figure 4, the Working Group illustrates a possible steady-state implementation of the 15-year plan—excluding AXAF costs—for the years 1999 through 2008. The illustration incorporates the following features (all costs in FY 1993 dollars):

- Funding for Research and Analysis, Mission Operations and Data Analysis, and international participation is maintained at fixed levels in real terms, preserving program continuity and ensuring steady and predictable support. In the Figure 4 illustration, these activities total $30 million per year—approximately the actual total for X-ray astronomy in FY 1993. The Working Group has not attempted to distribute the funding among these activities because their individual needs may vary and require periodic adjustments. (Note that XTE is in the operations phase after launch in 1995.)
- A small mission (e.g., an Explorer) is initiated every 3 years; a $60-million MIDEX mission alternates with a $30-million SMEX mission, providing program balance and continuity as well as frequent and rapid access to space for new instruments previously tested on balloon and rocket flights.
- A modest mission (e.g., an X-ray "Observer") is initiated every 5 years; a $150-million "Observer" mission alternates with a $250-million "Observer" mission, again providing balance and continuity as well as two flight opportunities per decade for substantial experiments.

Funding profiles in the Figure 4 illustration assume that expenditures are spread evenly over the development time period of the mission, so that the steady-state budget in constant dollars fluctuates between $70 and $100 million per year. However, the use of more realistic funding profiles should not change the basic picture: this scenario could be implemented for a steady-state funding level of about $85 million per year in FY 1993 dollars.

In Figure 5 (again, in FY 1993 dollars), the spending profile of Figure 4 is added to the currently projected development and operations costs of AXAF-I for the years 1996 through 2008. In this illustration, there would be five new starts for small (Explorer) and modest ("Observer") NASA X-ray missions during the decade 1999-2008, in addition to steady funding for R&A, MO&DA, and international missions. However, the steep reductions in AXAF-I costs toward the end of this time period would permit a vigorous NASA X-ray astronomy program to continue at a steady-state level of about $135 million per year in FY 1993 dollars—a realistic target to maintain the vitality of the field.

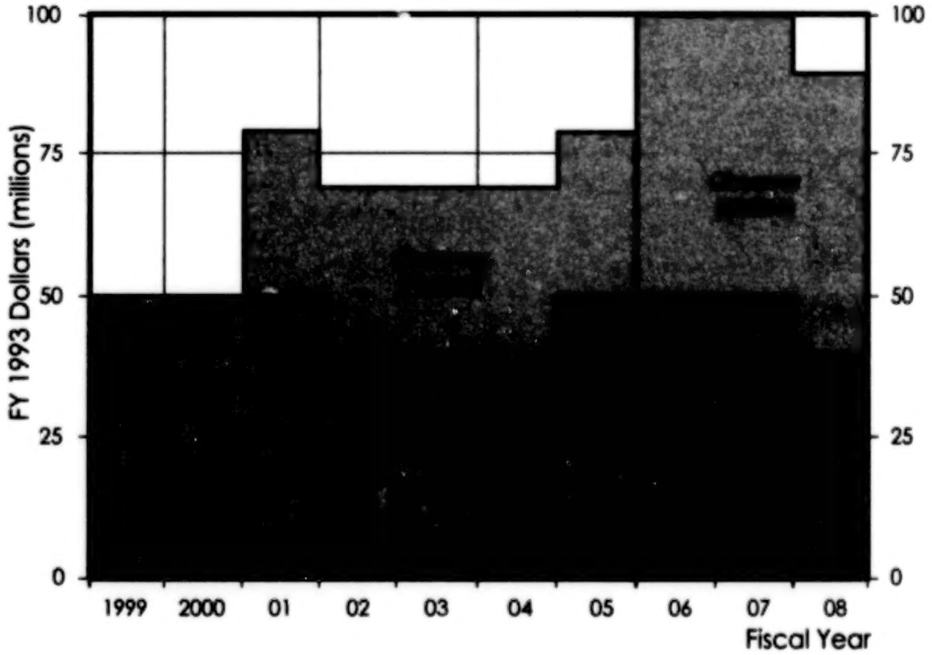


Figure 4. STEADY-STATE FUNDING PROFILE FOR X-RAY ASTRONOMY RECOMMENDED BY THE WORKING GROUP. Such funding is needed to provide sustained support for small and moderate missions, international participation, and vital R&A and MO&DA support programs. Costs of major missions, such as AXAF, are not included in this illustration.

Of course, the actual date for the termination of AXAF-I operations is not known; the AXAF-I design lifetime of 5 years could well extend to 10 years, during which this facility would remain the premier X-ray observatory for high-resolution imaging and spectroscopy. The dates shown in Figure 5 are therefore meant to be illustrative rather than definitive. However, a steady-state X-ray astronomy funding level of $135 million per year at the end of the next decade would permit NASA to pursue a number of important initiatives beyond 2004, including a possible AXAF Extended Mission, augmentation of funding for Advanced Technology Development, and detailed studies of future missions, such as an AXAF successor.

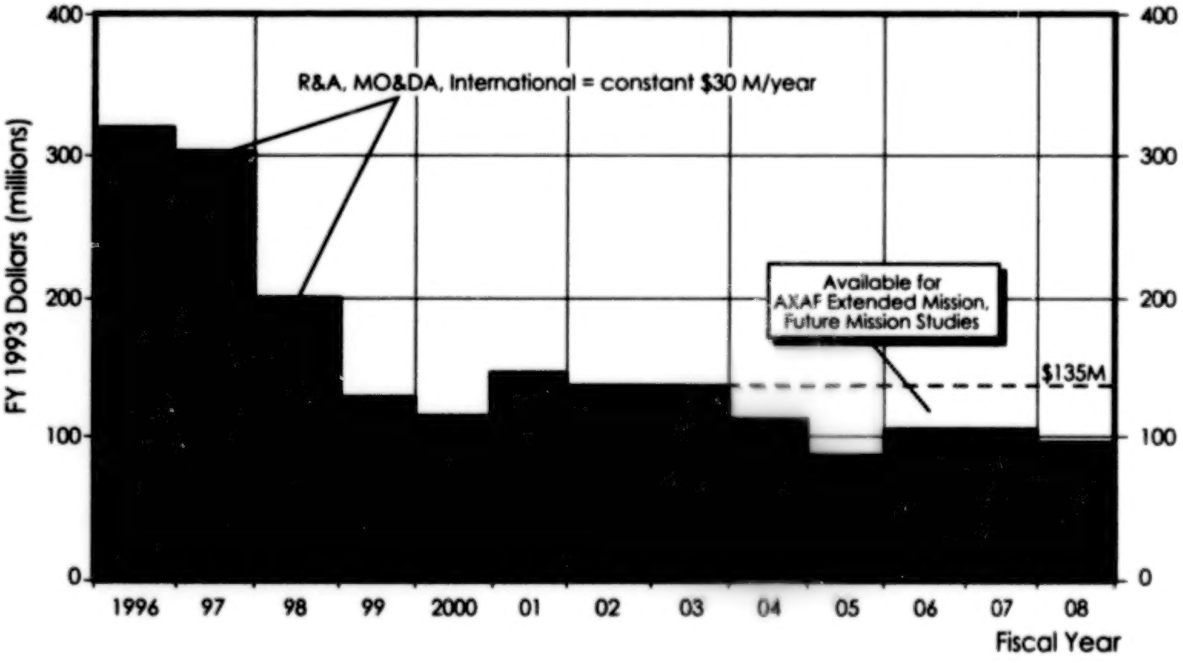
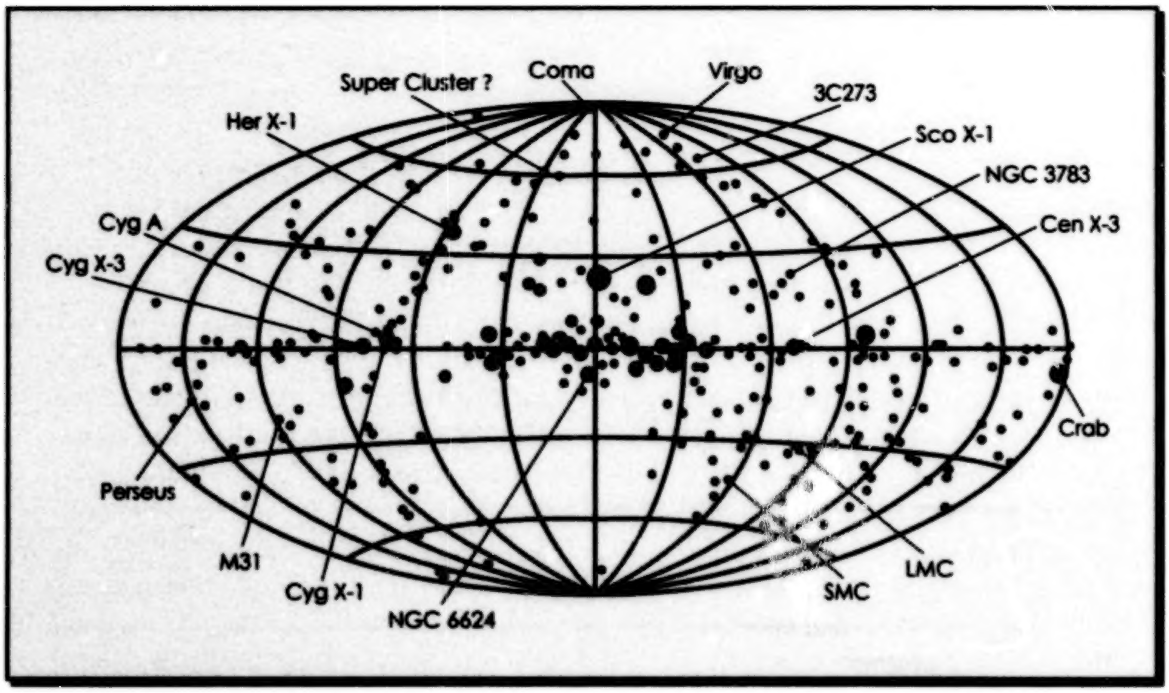


Figure 5. LONG-TERM BUDGET FOR X-RAY ASTRONOMY REQUIRED TO IMPLEMENT THE RECOMMENDATIONS OF THE WORKING GROUP through the year 2008. This budget, which combines AXAF costs with the steady-state funding profile of Figure 4, proposes level-of-effort funding of $135 million per year for FY 2004 and beyond.


Super Cluster ?
Coma
Virgo
3C273
Her X-1
Sco X-1
NGC 3783
Cyg A
Cen X-3
Cyg X-3
Crab
Perseus
M31
Cyg X-1
NGC 6624
SMC
LMC

FIRST ALL-SKY MAP OF COSMIC X-RAY SOURCES was compiled by the pioneering SAS-1 (Uhuru) satellite, launched in 1970.

Introduction

Since its inception in 1962, celestial X-ray astronomy has played a special role in astrophysics. X-rays serve as pointers to matter at high temperatures, to motions at speeds approaching that of light, and to the intense electromagnetic and gravitational fields characteristic of the most energetic cosmic phenomena.

Gamma rays often arise under these conditions as well. However, X-rays are usually emitted at much greater intensity and are more easily detected and imaged. Extreme-ultraviolet radiation is also a marker of cosmic violence. Such emission, however, is heavily absorbed by neutral hydrogen in the plane of our Galaxy, which blocks detection of most extreme-ultraviolet sources more than a few hundred light-years away. Although observations at ultraviolet, visible, and longer wavelengths can indirectly reveal the presence of high-energy phenomena,

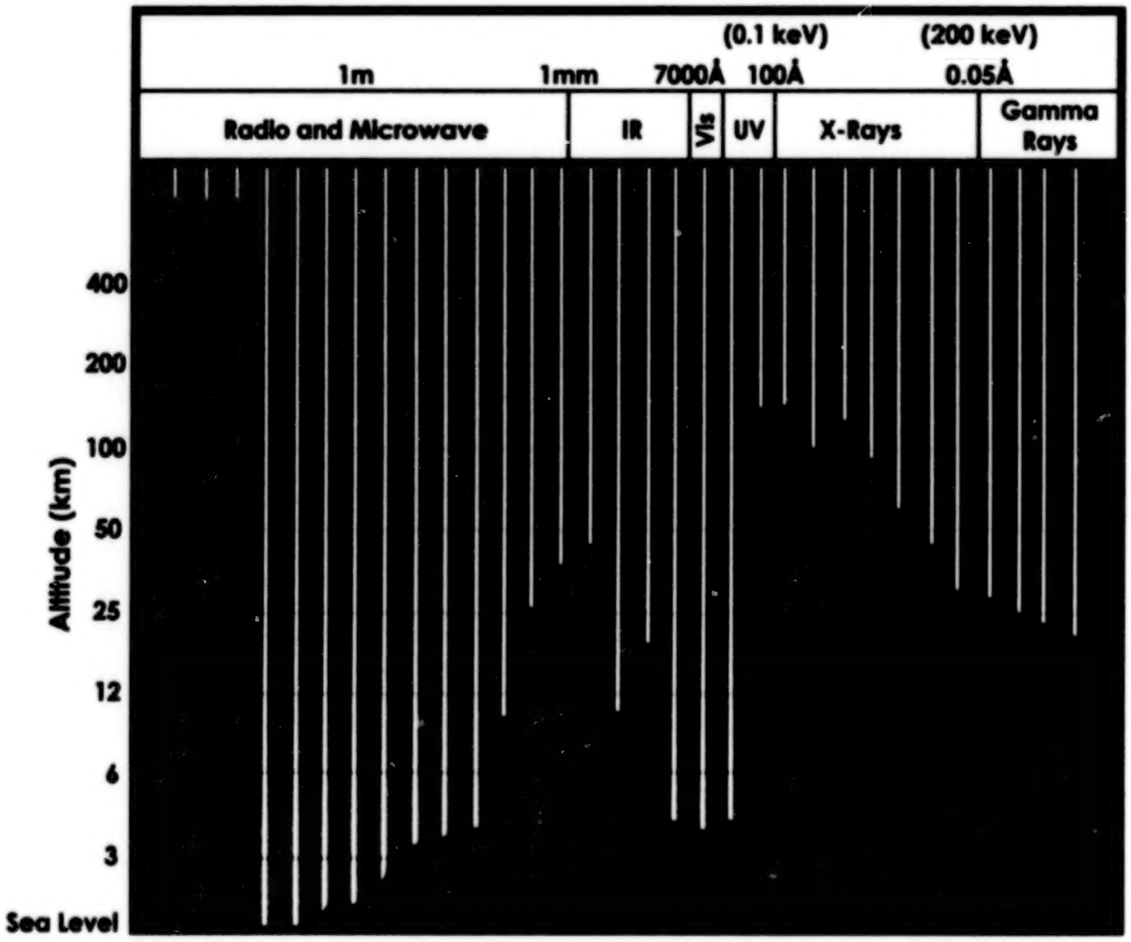


Figure 6. OPACITY OF THE EARTH'S ATMOSPHERE restricts ground-based observations of cosmic electromagnetic radiation to the visible band, the radio band, and a few submillimeter and infrared wavelengths. The X-ray band, extending from 100 Å (0.1 keV) down to 0.05 Å (200 keV), must be studied from space.

they do not usually permit detailed study of the physics that underlies the emission mechanisms. X-ray astronomy thus remains our most fundamental and powerful tool for exploring the high-energy Universe.

The decade of the 1990s promises a new series of observations in this key field. After a hiatus of more than a decade, long-lived U.S. satellites will once again begin to return data on the structure, composition, motions, and temporal variability of X-ray sources. These important new observing opportunities will be supplemented by U.S. scientific participation in a number of international X-ray missions.

Following a brief history of celestial X-ray astronomy, this report describes the approach of the X-Ray Astronomy Program Working Group in developing a 15-year plan for NASA's X-ray astronomy program covering the period 1994-2008.

1.1. CELESTIAL X-RAY ASTRONOMY: THE FIRST THREE DECADES

Extraterrestrial X-rays were first detected in 1949. A group of scientists at the Naval Research Laboratory (NRL) in Washington, D.C., using Geiger counters flown aboard a V-2 rocket, recorded X-rays from the Sun; such emission had been postulated a decade earlier to explain the effect of solar flares on radio transmissions. This discovery spurred two decades of rocket investigations into solar X-rays, led mainly by the NRL group and by British and Canadian scientists.

X-rays from more distant sources were not detected until 1962, when a research team at American Science and Engineering (AS&E), Inc., in Cambridge, Massachusetts, working under the sponsorship of the U.S. Air Force, carried out an Aerobee rocket experiment ostensibly intended to investigate solar X-rays scattered from the Moon. Two flights had ended in failure. But a third flight, scanning the moonlit sky with specially developed Geiger counters of unprecedented sensitivity and field of view, detected a brilliant X-ray source in the southern constellation Scorpius. Moreover, when pointed anywhere in the sky, the detectors always returned higher count rates than when pointed toward the Earth. The pioneering AS&E flight had discovered not only Scorpius X-1—now known to be the brightest accretion-powered X-ray binary star in the sky—but also evidence for a diffuse cosmic X-ray background radiation, whose origin remains one of the central unanswered questions of astrophysics.

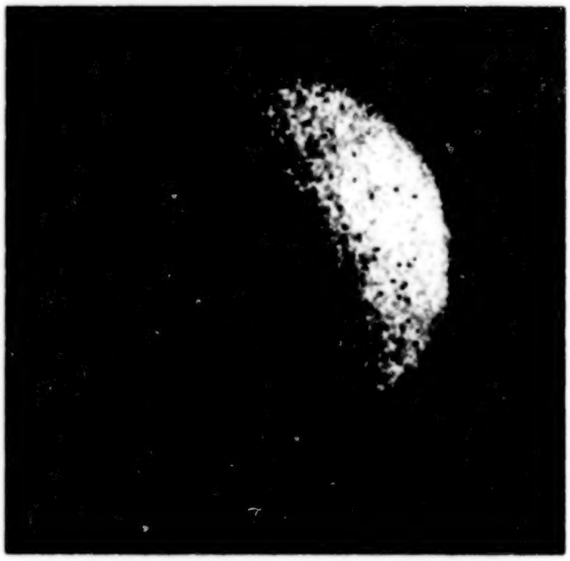


Figure 7. SUNLIT SIDE OF THE MOON glows in scattered solar X-rays first imaged by ROSAT in 1990. Dark side appears even darker than sky because the cosmic X-ray background radiation is occulted.

Nearly three decades later, an X-ray telescope aboard Germany's Roentgen Satellite, ROSAT, would return an image of the quarter Moon (Figure 7). The sunlit portion of the lunar surface would indeed be seen to glow faintly with scattered solar X-rays—at an intensity far below that which could have been detected in 1962.

In 1963, an NRL rocket experiment detected a second discrete X-ray source, later identified as the Crab Nebula, the remnant of the supernova of 1054. X-rays are emitted by clouds of high-energy electrons gyrating in the intense magnetic field of the central neutron star.

During the 1960s and 1970s, numerous satellites capable of celestial X-ray observations were placed into orbit by the United States, the Soviet Union, the western European nations, and Japan (Figure 8):

- Four NASA Orbiting Solar Observatories (OSO-3, 6, 7, 8);
- The European Space Research Organization's ESRO-2B satellite;
- The *Vela* series of satellites (*Vela*-5A, 5B, 6A, 6B) launched by the U.S. Air Force, primarily for the detection of nuclear explosions;
- NASA's first Small Astronomy Satellite (SAS-1, known as *Uhuru);*
- NASA's third Orbiting Astronomical Observatory (OAO-3, known as *Copernicus),* which carried a British X-ray experiment;
- NASA's Skylab research facility;
- The Dutch-built Astronomische Nederlandse Satelliet (ANS);
- The British *Ariel*-5 mission, which carried a U.S. experiment;
- NASA's third Small Astronomy Satellite (SAS-3);
- NASA's first and second High Energy Astronomical Observatories (HEAO-1 and HEAO-2, known as *Einstein);* and
- Japan's *Hakucho* X-ray observatory.

The most significant advances in X-ray astronomy were provided by *Uhuru,* the first satellite dedicated solely to extrasolar X-ray observations, and *Einstein,* the first imaging X-ray telescope in orbit. *Uhuru* was launched off the coast of Kenya in 1970 for the first all-sky survey at X-ray wavelengths. The results were published in four catalogs, the last of which (1978) listed 339 sources. NASA's HEAO-1 satellite carried out an even more detailed all-sky survey from 1977 to 1979.

The *Einstein* observatory, launched in 1978, opened another era in X-ray astronomy. It returned an extensive series of two-dimensional, high-resolution images of cosmic X-ray sources through the use of nested sets of grazing-incidence mirrors (Figure 9). The observatory carried out imaging and spectroscopy in the energy range from 0.2 to 4 keV until the depletion of its attitude-control

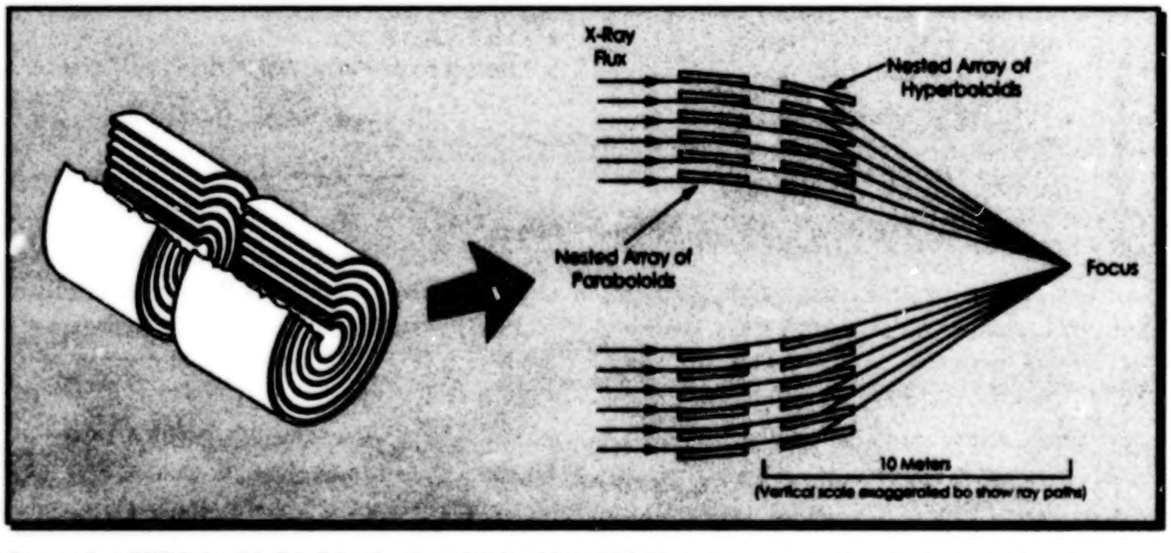
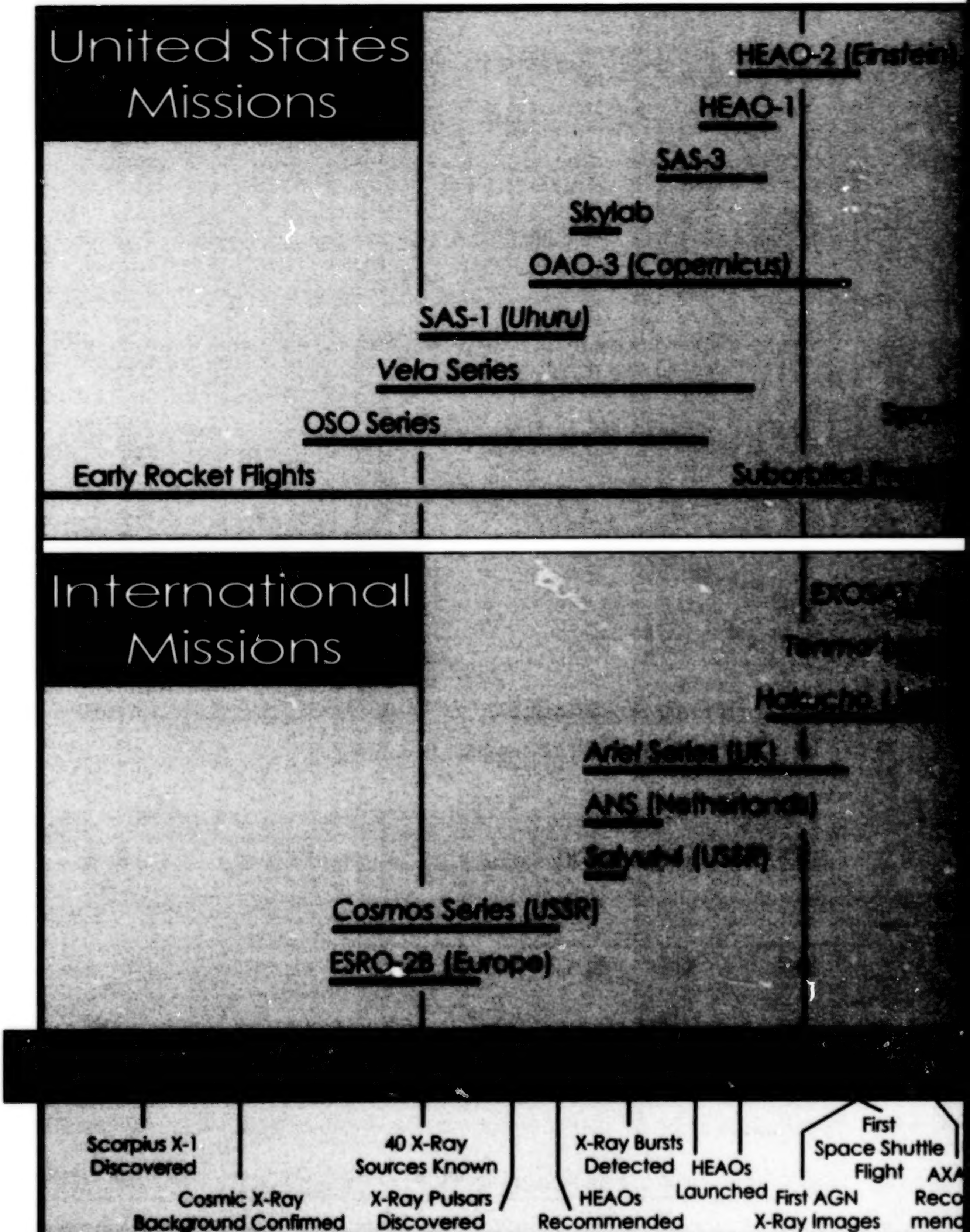
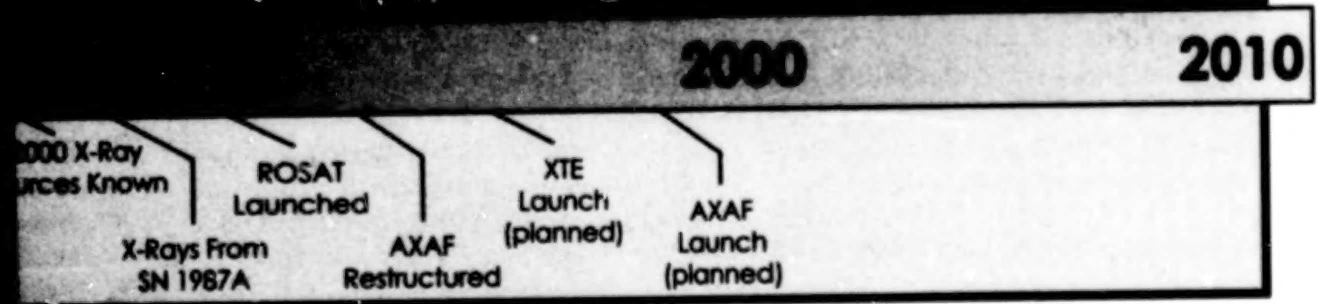

X-Ray Flux
Nested Array of Hyperboloids
Nested Array of Paraboloids
Focus
10 Meters
(Vertical scale exaggerated to show ray paths)

Figure 9. NESTED PAIRS OF GRAZING-INCIDENCE MIRRORS permit the precise focusing of X-rays.

FIGURE 8: X-RAY ASTRONOMY, 1960-2010




2000
2010
000 X-Ray
rces Known
X-Rays From
SN 1987A
ROSAT
Launched
AXAF
Restructured
XTE
Launch
(planned)
AXAF
Launch
(planned)

thruster gas in 1981. By that time, however, the number of known X-ray sources had risen to more than 1,000. More importantly, the *Einstein* observations confirmed that X-rays are emitted by virtually every known class of astronomical object or system, from ordinary stars to supernova remnants (Figure 10), the interstellar medium, galaxies, galaxy clusters, and active galactic nuclei (AGN).

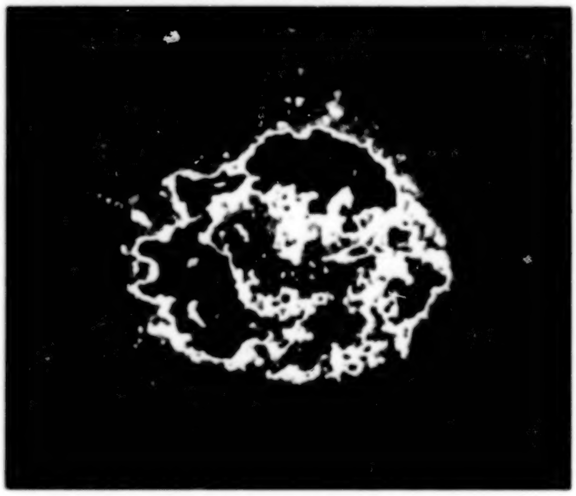


Figure 10. CASSIOPEIA-A SUPERNOVA REMNANT was among the hundreds of X-ray sources imaged by the Einstein observatory, the first imaging X-ray telescope in orbit.

There then began a long hiatus in U.S. X-ray astronomy missions broken only by brief Space Shuttle flights of three experiments. These were the Spartan-1 X-ray instrument in 1985, the Broad Band X-Ray Telescope (BBXRT) in 1990, and the Diffuse X-Ray Spectrometer (DXS) in early 1993.

Fortunately, U.S. participation in international missions has helped to fill this data void. These include the European Space Agency (ESA) X-Ray Observatory Satellite (EXOSAT, 1983-1986); the Japanese *Ginga* satellite (ASTRO-C, 1987-1991); ROSAT, launched in 1990, which has already proved to be the most productive X-ray mission since *Einstein;* and Japan's Advanced Satellite for Cosmology and Astrophysics (ASCA, formerly ASTRO-D), launched in 1993. International missions will be the only sources of new X-ray data until the flights of NASA's X-Ray Timing Explorer (XTE) in 1995 and Advanced X-Ray Astrophysics Facility (AXAF-I) in 1998.

1.2. APPROACH OF THE WORKING GROUP

The Working Group was originally chartered by NASA to develop a plan for X-ray astronomy for the period 1990-2005. This internal NASA study was timed to proceed in parallel with a more broadly based survey of astrophysical research opportunities for the 1990s then being conducted by the Astronomy and Astrophysics Survey Committee (the Bahcall Committee) of the U.S. National Academy of Sciences.

When the Bahcall Committee began its work, however, the future of NASA's X-ray astronomy program was far from certain. Although AXAF had been the top recommendation of the Academy's previous astronomy survey for the 1980s, Congress had not yet approved AXAF for development, and the approved XTE mission faced a series of delays for budgetary reasons. Research activity in X-ray astronomy had in fact begun to shift to Japan and Europe during the 1980s.

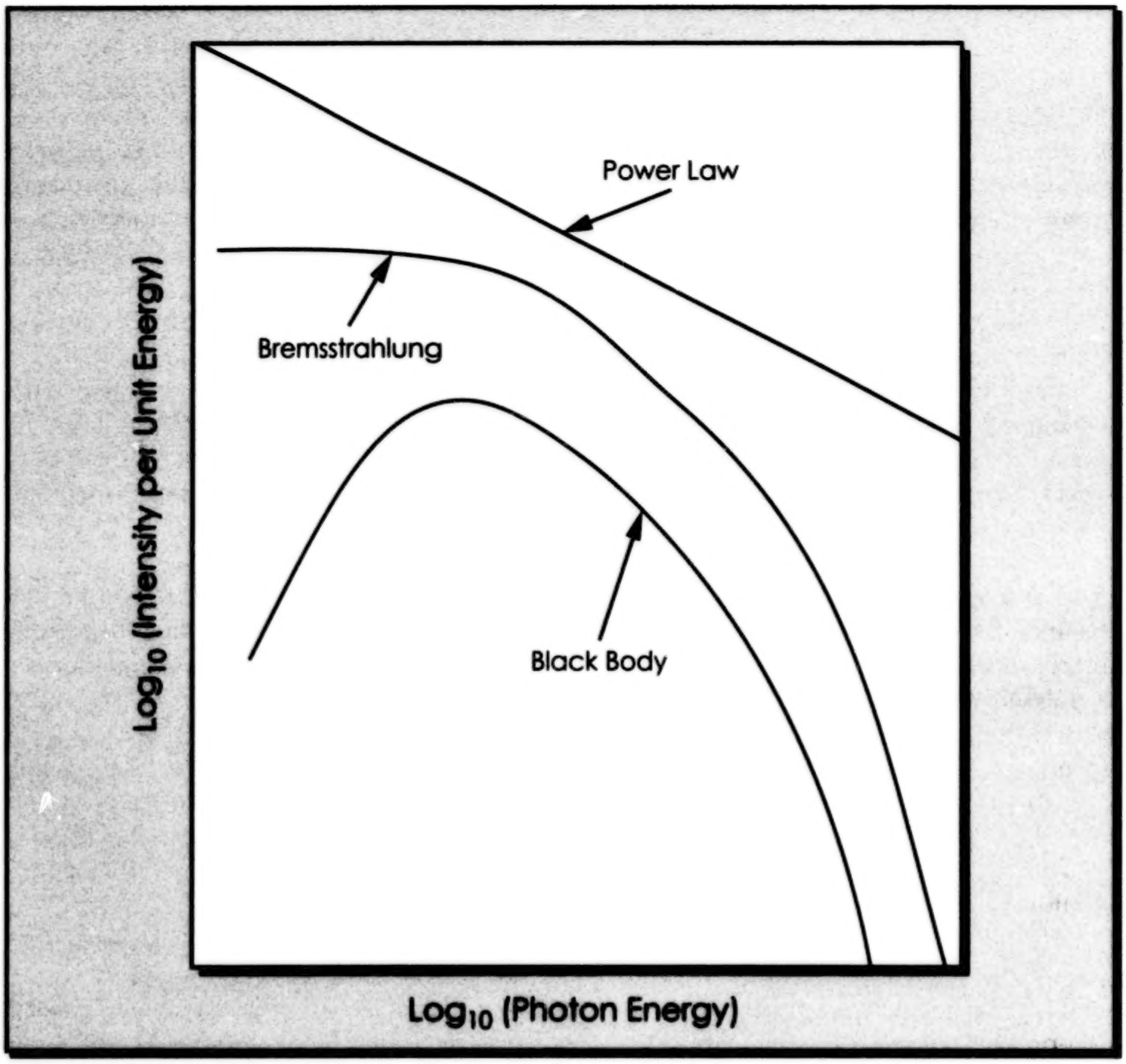
However, these factors provided a strong incentive to develop a new plan to revitalize NASA's X-ray astronomy program. After reviewing the most interesting and pressing scientific questions in astrophysics, which reaffirmed the importance of AXAF and XTE, the Working Group devoted considerable attention to the need for more modest missions of the type usually implemented through the Explorer program. Such new investigations, which could address a range of scientific problems, would also contribute to a balanced program of small, moderate, and large missions, providing stability to the field and more frequent access to space.

Subsequent Congressional approval of AXAF for development reflected continued technical progress in this key project and served to reinforce the strategic guidance provided earlier by the Academy and NASA's internal advisory groups. Moreover, opportunities for participation in international X-ray missions had increased during the 1980s. The Working Group concluded that NASA should strongly support such opportunities, provided they did not preempt the initiation of moderate- and small-class U.S. missions.

The Working Group also assessed the advances that would be needed in X-ray technology, theoretical and laboratory astrophysics, computation, data analysis, and archival research needed to support a vigorous flight program. The Academy decadal surveys had stressed the general importance of all of these, but it remained for the Working Group to identify specific areas of implementation and an appropriate programmatic structure.

Although the Working Group completed the bulk of its study in phase with the Bahcall Committee, the future of the Explorer program and of AXAF remained unclear. These uncertainties were resolved by the restructurings of the Explorer program in 1991 and AXAF in 1992. At that point, the High Energy Astrophysics Branch reconvened the X-Ray Astronomy Program Working Group to revise and update the plan that had been developed earlier. This report, based upon the status of NASA's Astrophysics program in early 1994 and reflecting the 1993 cancellation of the AXAF-S (Spectroscopy) spacecraft, presents a current plan for the period 1994-2008.

It is recognized that significant changes in NASA's science program are likely over this period, which will impact the implementation of the plan envisioned. The Working Group wishes to underscore the fact that the basic elements of a balanced program in X-ray astronomy will nevertheless remain unchanged.



SHAPE OF OBSERVED X-RAY SPECTRUM provides clues to cosmic emission mechanisms. Shape at low photon energy permits discrimination between hot plasmas that are optically thick (blackbody radiation) and optically thin (Bremsstrahlung); power-law spectra are characteristic of synchrotron radiation by electrons in magnetic fields.

2 Scientific Objectives of X-Ray Astronomy

This chapter summarizes the status of scientific investigations in six areas: stellar physics and evolution; endpoints of stellar evolution; the interstellar medium; galaxies; clusters of galaxies and large-scale structure; and cosmic X-ray background radiation. The discussion highlights scientific questions to which X-ray observations can provide critical insight and identifies the need for a variety of missions to address these questions.

2.1. STELLAR PHYSICS AND EVOLUTION

Stellar evolution is a cyclic process. Gas in a dense region of the interstellar medium (ISM) is cooled by dust, compressed into a protostar by gravity, heated and altered in the stellar core by nuclear fusion, and finally returned to the ISM by an explosive ejection or a stellar wind, to be recycled in the next generation of stars (Figure 11). Some matter remains trapped in slowly evolving low-mass stars that have nuclear-burning lifetimes greater than the estimated age of the Galaxy, and some is trapped within ultra-dense stellar remnants, governed by the laws of relativistic physics. X-rays are produced at virtually every stage in this cycle.

2.1.1. Young Stars

Einstein revealed that newly forming stars of the T-Tauri type, found in association with molecular clouds, are bright X-ray sources. The X-ray emission apparently arises from the dynamo action of magnetic fields trapped in the accreting plasma, which somehow converts kinetic energy into thermal energy.

The *Einstein* data permitted astronomers to begin to understand the operation of these processes and their influence on the early development of a star and its planetary system. Improved measurements of the spectra and variability of T-Tauri stars, in coordination with observations at other wavelengths, are being made by ROSAT and ASCA.

Even these facilities, however, will not make possible the systematic surveys at high spectral resolution required to explore fully the X-ray emission from T-Tauri stars. A long-lived observatory for stellar X-ray spectroscopy with a spectral resolution of 10,000 or better will be required to measure line profiles, Doppler shifts, and ionic compositions. One can envision, for the era beyond AXAF, the possibility of milliarcsecond imaging that could reveal directly the spatial structure and spectral features of the regions of X-ray emission that may surround the nearest of these young stars.

2.1.2. Main-Sequence Stars

After the onset of nuclear fusion in its core, a new star reaches an equilibrium that can be represented by a point on the so-called "main sequence" of a diagram that relates luminosity to surface temperature (or equivalently, to color or to spectral type). A star spends most of its life on the main sequence. Near the end of its nuclear-burning lifetime, however, it undergoes a series of changes that diminish both temperature and luminosity, so that its representative point moves away from the main sequence.

No main-sequence star has a surface temperature high enough to generate significant thermal X-radiation. However, *Einstein* detected X-rays from stars throughout the main sequence. This showed that X-ray emitting plasmas must be present in the coronae of such stars (above the much cooler surface layers) during most of their nuclear-

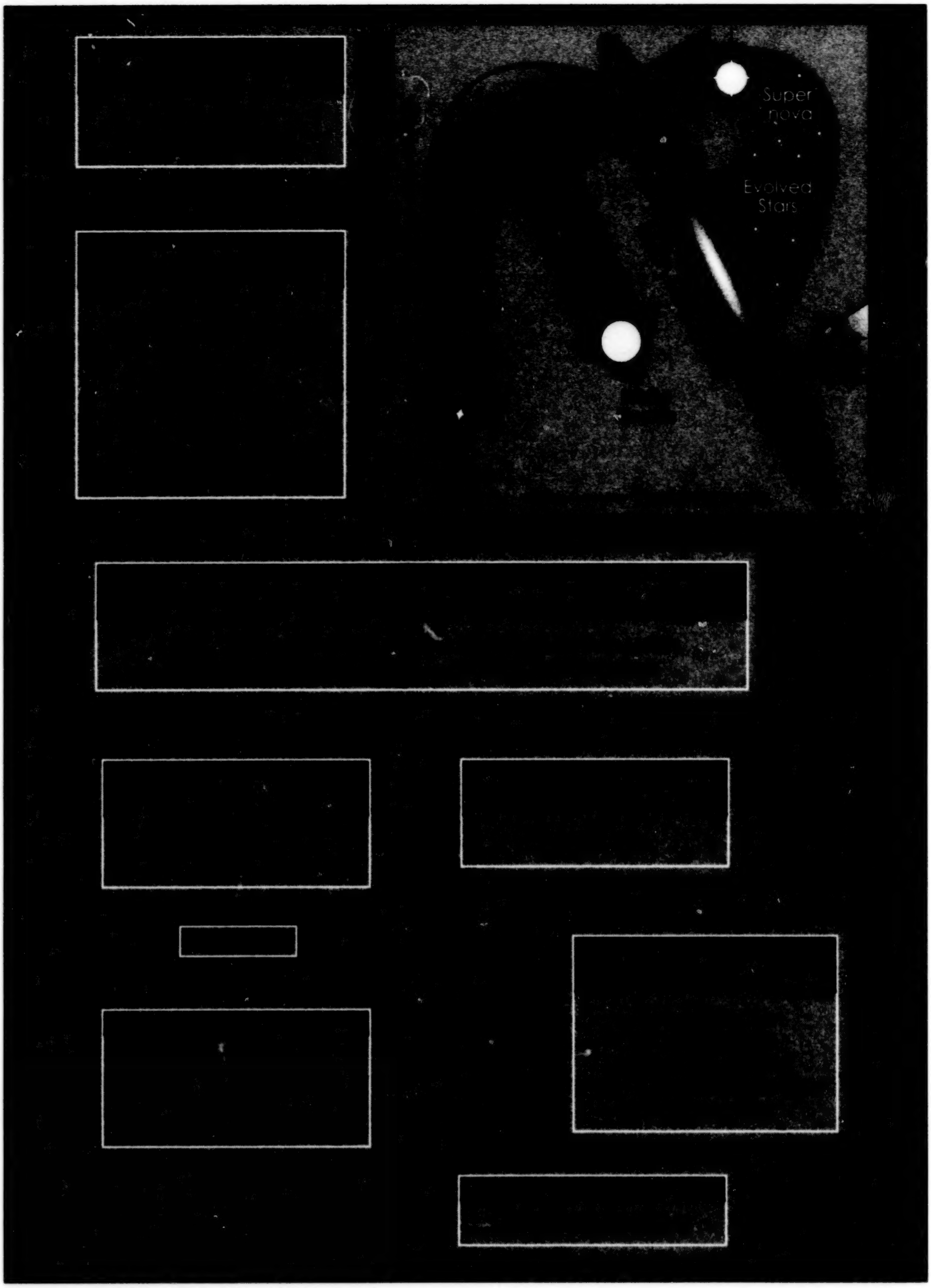


Figure 11. X-RAYS ARE EMITTED AT VIRTUALLY EVERY STAGE OF STELLAR EVOLUTION, as illustrated in this schematic flow-chart of the evolutionary sequence. The general path of this progression in a temperature-luminosity diagram is suggested in the inset at upper right.

burning lifetimes. More than a decade later, we still have only a preliminary understanding of the mechanisms that can transport energy into the hot plasma of the outer atmosphere.

Low-Mass Stars

In the nearest star, the Sun, high-resolution spectroscopy has identified and measured the lines of many ionic species and made possible the application of sophisticated plasma-diagnostic techniques to an analysis of physical conditions in the corona. Even so, the mechanisms responsible for heating the solar corona are still not completely understood.

Rocket and satellite investigations since the 1950s have measured the highly variable X-rays from the solar corona (Figure 12); these constitute only 10^{-6} of the solar luminosity but are sufficiently intense to ionize the Earth's upper atmosphere (perturbing and sometimes disrupting radio communications). In the early 1970s, high-resolution images from the Skylab X-ray telescope traced a complex pattern of X-ray emission over the solar surface. They also revealed intricate correlations between the emission and surface magnetic activity.

Explanations of such X-ray emission have focused on the mechanical transport of energy upward from the photosphere through plasma instabilities, shock-wave heating, or other means, followed by thermalization. However, such approaches cannot readily explain the sharply defined temperature transition that separates the photosphere from the corona.

A recently revived alternative theory overcomes this difficulty by postulating a nonthermal velocity distribution in the photospheric plasma; X-ray emission arises because of the filtering of high-velocity ions into the corona. The accuracy of this model, which also predicts an abrupt temperature inversion, could be tested through detailed observations of X-ray emission from normal, low-mass stars with different radii and surface gravities.

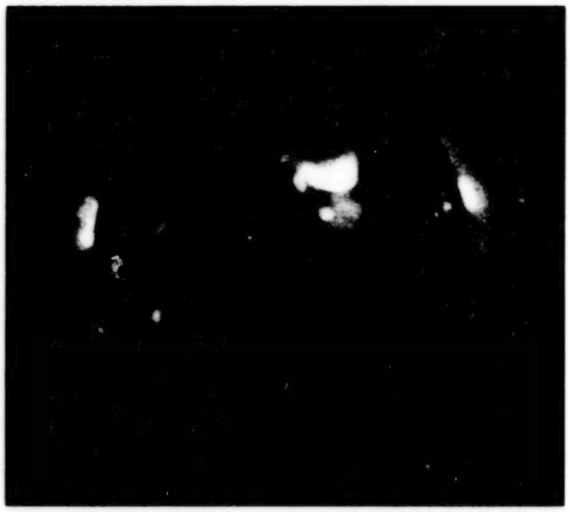


Figure 12. COMPLEXITY OF SOLAR CORONAL X-RAY EMISSION is revealed with unprecedented clarity in this image recorded by a U.S. telescope aboard Japan's Yokoh solar X-ray observatory.

The *Einstein* observatory opened up the field of comparative coronal studies by detecting X-rays from the very nearest Sun-like stars, which are fainter by factors of 10^{11} or more because of their distances. Exploratory surveys suggest that all main-sequence stars of less than three solar masses have coronae with X-ray emission that is correlated with rotation speeds.

Systematic studies of larger samples, drawn from ROSAT and ASCA observations, will produce major advances in our general understanding of stellar coronae. Spectroscopy of nearby stars with AXAF will begin the measurement of line strengths needed to determine the composition, density, and temperature of the emitting gas. Nevertheless, the spectral measurements required for complete plasma X-ray diagnostics and Doppler velocity determinations will not be possible until high-sensitivity, ultrahigh-resolution X-ray spectroscopy becomes available.

High-Mass Stars
A major surprise of the *Einstein* observations was the discovery of intense X-ray emission from the rare O-type stars, the most massive and luminous stars of all. Standard stellar-structure theory predicts that the interiors of such stars should be free of the subsurface convective turbulence thought to be essential to the generation of X-ray emitting coronae in solar-type stars.

Rocket ultraviolet spectroscopy during the 1960s, however, revealed the universal existence in such stars of massive, supersonic winds driven by radiation pressure and carrying away surface material at rates as high as ten solar masses per million years. Although the average temperatures of the winds are too low to generate the observed X-ray fluxes, some of the rocket spectra showed the presence of anomalous ionic species indicative of localized higher temperatures.

The *Einstein* observations demonstrated the ubiquity of X-rays from O stars and showed that they constitute typically about 10^{-6} of the total O-star luminosity, which is, coincidentally, the fraction characteristic of solar-type stars. Current thinking holds that O stars generate X-rays in transient "hot spots" heated by radiation-driven shock waves in their supersonic winds. This conjecture could be tested by time-resolved, high-resolution X-ray spectroscopy that would search for evidence of rapid temperature fluctuations in the emitting regions.

RS CVn Binaries
Most stars are found in binary systems. They are bound to companions by mutual gravitational attraction in orbits with periods that range from a few hours to tens of thousands of years. Short-period binaries, in particular, may be in a close orbit in which violent magnetohydrodynamic activity is stirred by orbital motion.

This appears to be the case for the short-period RS CVn binary systems, which display particularly high levels of coronal X-ray emission. Unraveling the complexities of their X-ray phenomena will challenge the observing capabilities of the 1990s. This task may ultimately require imaging with an angular resolution sufficient to reveal the spatial distribution of X-ray emission in the envelope of material common to the two component stars.

2.2. ENDPOINTS OF STELLAR EVOLUTION

The gravitationally collapsed products of stellar evolution—white dwarfs, neutron stars, and black holes—are an especially rich field for X-ray studies. They are, in effect, cosmic laboratories that permit the study of physical processes in intense gravitational and electromagnetic fields over an enormous range of matter densities.

The processes that produce these objects are also of intense interest. Supernovae, for example, inject enormous amounts of energy (together with moderate amounts of mass) into the interstellar medium and generate much of the hot gas observed by X-ray telescopes. Indeed, X-ray astronomy has provided most of our current knowledge of the physical conditions of the hot gas within supernova remnants. Although most observed supernova remnants lie within our own Galaxy, X-rays from an extragalactic supernova were first detected in 1980. Additional extragalactic remnants have now been observed by ROSAT and ASCA.

2.2.1. Isolated Stellar Remnants

In stars of less than a few solar masses, the nuclear-burning phase ends after a few billion years with the ejection of the outer layers. The core of fusion products is then exposed as a white-dwarf star. This Earthsized remnant has a mass generally less than that of the Sun, a density on the order of 10^6 gm/cm^3, and, in the early stages of cooling, a surface temperature high enough to produce significant X-ray emission at 0.25 keV.

In more massive stars, the mass of the fusion products may exceed the Chandrasekhar limit of 1.4 solar masses, at which point electron pressure can no longer support the core against its self-gravity. The resulting sudden collapse then triggers a supernova explosion and a core implosion that forms a rapidly spinning, strongly magnetized neutron star. With a radius of about 10 km and approximately the Chandrasekhar mass, the neutron star will appear as a radio pulsar for a few million years—and, in its early stage of rapid rotation, as a rapid X-ray pulsar as well.

Most relativistic theories of gravity, including Einstein's General Theory of Relativity, predict that a still more massive star will implode into a black hole—a superdense object from whose surface even light cannot escape. In isolation, a black hole is thought to be truly black—invisible except for the effect of its gravitation in deflecting light and matter that pass nearby.

2.2.2. Stellar Remnants in Binaries

Unlike an isolated star, a collapsed star in a close binary system (Figure 13) can draw matter from its companion and enter a second life as a brilliant, long-lived X-ray source. As matter falls into the deep gravitational potential well of the collapsed star, its kinetic energy is converted into heat and radiated away. In the case of a neutron star or black hole, each accreted atom yields an energy of several hundred MeV.

The accretion rate, limited by the outward pressure of this radiation, cannot exceed about one solar mass every 10^8 years. However, that rate can sustain an X-ray luminosity equivalent to 10^5 Suns, yielding a

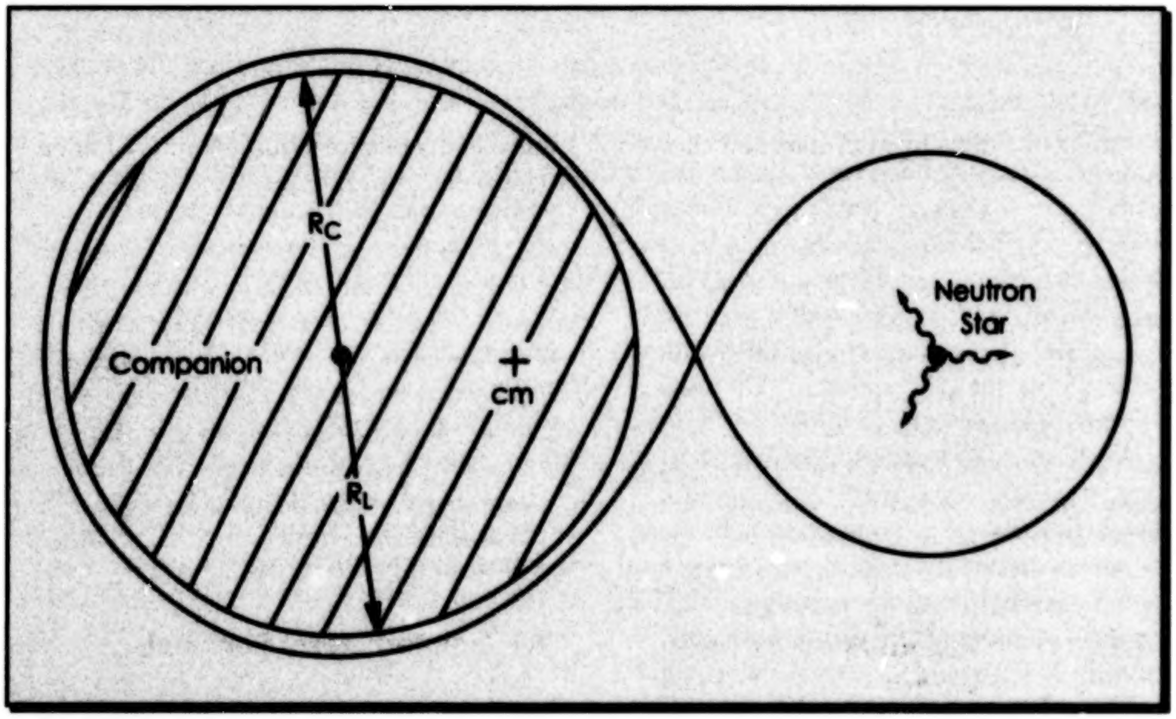


Figure 13. STRUCTURE OF X-RAY BINARY SYSTEM is illustrated in this schematic model of a neutron star and a main-sequence dwarf companion, viewed from above the orbital plane. The companion (hatched region) and the more massive neutron-star primary are shown encircled by their critical potential lobes.

source readily detectable anywhere within the Local Group of galaxies by an X-ray telescope of the ROSAT class. Some 100 such sources are already know in our own Galaxy, together with some 300 sources in neighboring galaxies. These objects exhibit remarkable variations on the central theme of accretion-powered X-ray binaries.

High-Mass X-Ray Binary Pulsars

A typical high-mass X-ray binary pulsar is a short-lived system located in a galactic spiral arm in a region of active star formation. The primary star is a supergiant of about 20 solar masses with an optical-ultraviolet luminosity of 10^6 Suns and an intense supersonic wind. The companion is a 1.4-solar-mass neutron star with a radius only one-millionth that of the primary. The orbital period is about 2 days.

Having been formed only recently by the supernova outburst of a similarly massive progenitor, the neutron star has retained most of its initial high magnetization. It can therefore channel a portion of its companion's outflowing wind through an accretion disk to hot spots at its magnetic poles (generally located well away from the rotational poles). Emanating from the hot spots with a luminosity rivaling the total optical-ultraviolet luminosity of the primary, X-ray beams sweep around the sky like lighthouse beacons, producing the X-ray pulsations that are seen by a distant observer. The matter accreted onto the hot spots quickly fuses into heavier elements, augmenting the total power radiated by about 1 percent.

Cyclotron-resonance absorption lines have been detected in the X-ray spectra of several X-ray pulsars in the energy range from 10 to 100 keV, demonstrating the presence of extremely high neutron-star surface magnetic fields. These observations have stimulated theoretical studies of Compton scattering in relativistic plasmas. Such studies predict the forms of cyclotron absorption lines and their dependence on the direction of emission, together with significant pulse phase-dependent spectral features that cannot be adequately investigated with current large-area detectors or even by the scheduled XTE mission. Future progress in exploiting this opportunity to explore the extremes of relativistic plasma physics would be facilitated by detectors with moderate energy resolution in the range from 10 to 100 keV, and collecting areas on the order of 1 m^2.

Phase fluctuations in the periodic variations of an X-ray pulsar can, in principle, reveal internal structural and dynamical features of the neutron star. These features are governed by the quantum mechanics of nuclear matter on a scale inaccessible to laboratory investigation. The search for such effects is one of the goals of XTE. However, future progress in the detection and analysis of these effects will require detectors of much larger area, e.g., in the range of 10 to 100 m^2.

Low-Mass X-Ray Binaries

A typical low-mass X-ray binary is a long-lived system generally found in the company of ancient, low-mass stars in the Galactic bulge or in a globular cluster. The system contains a dwarf star of less than one solar mass, together with an old neutron star with a magnetic field too weak to channel accreting matter onto its magnetic poles. Matter shed by the dwarf star thus settles across the entire surface of the neutron star, generating isotropic X-ray emission with no detectable modulation by rotation.

At the relatively lower temperature of this process, the accreted matter can accumulate, unfused, to a depth of several meters. After a few hours, a flash of thermonuclear fusion surges through the layer, suddenly releasing energy equivalent to a week of solar output and raising the surface temperature to 10 million degrees. The surface then cools through emission of a 10-second burst of X-rays.

In one remarkable object of this type, the so-called Rapid Burster, the accretion flow is interrupted quasi-periodically, apparently by a magnetic "gate" in the accretion flow. As a result, two kinds of X-ray bursts are observed. The first kind arises from the sporadic release of gravitational energy when the magnetic gate is opened and shut, which may occur at a rapid-fire rate of several times per minute. The other kind, which occurs less frequently, arises from the thermonuclear detonation of the layer of accreted matter.

High-resolution and high-throughput time-resolved spectroscopy of thermonuclear X-ray bursts could reveal emission lines shifted and broadened by the Doppler effect. These improved observations could thus provide direct measures of the radial expansion velocity of the X-ray emitting material momentarily lifted above the surface by radiation pressure. Such data would also throw new light on the complexities of quasi-periodic variations, including interesting correlations with radio emission.

2.2.3. Black Holes

Black holes are perhaps the most interesting and challenging targets of stellar X-ray observations. Stellar-mass black holes might be found, for example, in those X-ray binaries whose compact components have masses greater than three solar masses—the theoretical upper limit for the stability of a neutron star against gravitational collapse. Apart from inconclusive evidence for supermassive concentrations of matter at the centers of some external galaxies, the case for the existence of black holes rests primarily on the discovery of several such nonperiodic and rapidly variable X-ray binary systems.

Yet to be found, however, is any observational signature that can be unambiguously identified with the warping of space-time near the event horizon, an effect predicted by the General Theory of Relativity. This space-time warping might be manifested, for example, by rapid changes in the spectrum or polarization of X-rays emitted by the accreting clouds of plasma as they plunged toward the event horizon.

A promising place to look for such effects would be at the trailing edges of the millisecond X-ray emission spikes from Cygnus X-1 and other black-hole candidates. In order to achieve the requisite sensitivity, however, these observations will require detectors of very large collecting area and at least moderate spectral resolution—and probably also the superposition of data from many emission spikes measured with microsecond temporal resolution. A search for black-hole signatures will be pursued with XTE, but a detector of much larger area may be required.

Black holes may also have specific signatures in the hard X-ray and low-energy gamma-ray spectral regions. Hard X-ray continuum spectra can provide measures of apparent temperatures, which furnish constraints on the mass-to-radius ratio. Pair-plasma emission at the electron-positron annihilation energy of 511 keV may also be characteristic of black-hole candidates such as Cygnus X-1.

In the potentially important area of X-ray polarimetry, only exploratory measurements with inefficient detectors have been carried out up to now. However, recent advances in X-ray polarimetry have opened the way to substantial improvements in sensitivity and, therefore, hold promise for progress in the search for a black-hole signature.

2.2.4. Supernova Remnants

A supernova remnant (SNR) results from the interaction of the exploded star with surrounding material—first with circumstellar matter, and then with the interstellar medium. Because of the continuous evolution from an intense explosion into an ISM feature, studies of supernovae and SNRs convey much information about stellar evolution and about the physical, chemical, and dynamical state of the interstellar medium.

The *Einstein* observatory provided important new insights into the X-ray emitting gas in the SNR interior. ROSAT, which yields good spatial resolution, and ASCA, which furnishes good energy resolution, are now providing a more detailed picture of the composition and evolution of SNRs.

The next generation of X-ray satellites, however, will study SNRs with both high spatial and spectral resolution. Improved spatial resolution will permit more detailed views into the remnants at all stages in their evolution, but especially in the early stages that mark the transition from supernova to SNR. Such observations will reveal the sites of X-ray emission from the interaction with the circumstellar material and from the inward-moving reverse shock wave.

Improved spectroscopy will enable us to determine more precisely how supernovae enrich the ISM. Spectroscopic observations will help to reveal what old stars—the progenitors of supernovae—were like at the ends of their stellar lifetimes. Observations of old remnants, barely distinct against the Galactic X-ray background, will allow us to piece together the process of ISM regeneration. Properly interpreted, future X-ray observations of both supernovae and SNRs should help to solve some of the current puzzles of both stellar and interstellar evolution.

2.3. THE INTERSTELLAR MEDIUM

The interstellar medium (ISM) is a complex system of mutually interacting constituents: gas, dust, cosmic rays, and magnetic fields. Ninety percent of the gas is hydrogen; the rest is helium, with a slight percentage of the heavier elements.

2.3.1. Interstellar Gas

Several distinct components of the interstellar gas have been identified: cold (about 10^2 K) clouds of neutral hydrogen gas containing even colder molecular clouds, where new stars are born; a hot (10^6 K or more) tenuous plasma, which fills most of the volume of the Galactic disk; and a warm (10^4 K) intercloud region, which lies at the interfaces of these regimes. The hot gas cools by emission of soft X-rays. Elucidation of its properties, and of its role in the evolution of stars and the Galaxy, is one of the principal tasks of X-ray astronomy.

Soft X-Ray Diffuse Background

Rocket and satellite experiments during the 1970s yielded all-sky surveys of the intensity of the soft X-ray diffuse background radiation in several broad spectral bands covering the energy range from 0.1 to 1.0 keV, with angular resolutions of a few degrees (Figure 14). Below the carbon K-edge at 0.28 keV, these maps reveal a complex intensity distribution; in broad outline, the emission is nearly constant around the Galactic equator but increases with Galactic latitude, roughly doubling in intensity from equator to poles.

The broad-band spectral data and their correlations with the column densities of neutral hydrogen demonstrate that most of the diffuse 0.25-keV radiation originates in a region less distant than the neutral hydrogen, i.e., in a cloud of hot gas that surrounds the Solar System. More recent ROSAT observations with higher spatial resolution have demonstrated that some of the high-latitude 0.25-keV radiation originates beyond the neutral hydrogen, in the halo of the Galaxy. The origin of the radiation at 0.75 keV, which can penetrate much greater thicknesses of the cool gas, remains unclear.

The ROSAT all-sky survey of the soft X-ray diffuse background has now revealed structures on angular scales down to 10-20 arcminutes over most of the sky and down

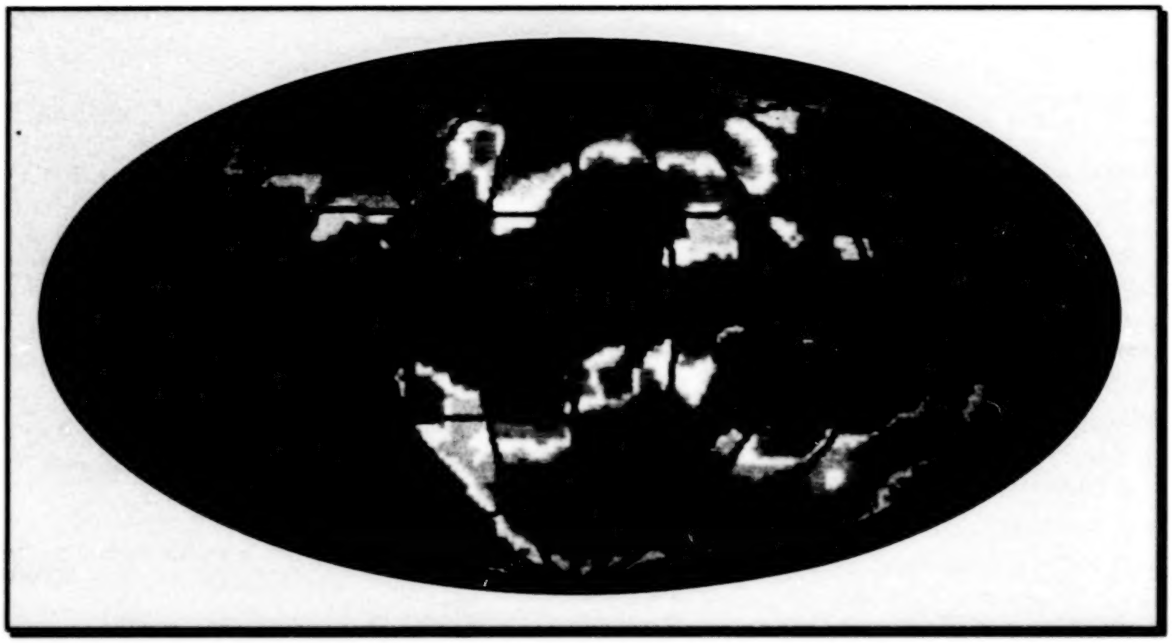


Figure 14. SOFT X-RAY DIFFUSE BACKGROUND AT 0.25 keV was mapped by a series of University of Wisconsin rocket flights during the 1970s.

to 2 arcminutes near the Ecliptic poles. The results will permit detailed correlation between the intensities of soft X-rays and the 21-cm radio emission of atomic hydrogen, which traces the morphology of the cold component of the interstellar medium.

The ROSAT telescope combination of good spatial resolution, wide field of view, and high ratio of signal to extraneous background was essential for this major stride forward in X-ray studies of the ISM. However, broad-band surveys with greatly improved angular resolution will be needed to reveal the interaction of the hot gas with the cold clouds and to distinguish discrete sources from the diffuse emission.

Properties of the cooler gas can be determined by high-resolution spectroscopy of absorption features in the X-ray spectra of more distant discrete sources and by the precise delineation of the obscuration of the diffuse X-ray background by nearby cool clouds. In particular, X-ray spectroscopy of distant sources by AXAF should reveal the K-shell absorption features arising from oxygen and other elements in cold interstellar clouds along the line of sight. Such measurements will permit reliable determinations of elemental and ionic abundances without the problems in the interpretation of optical-line strengths caused by uncertain knowledge of the physical conditions within the clouds. Comparative studies of the soft X-ray emission in other galaxies will clarify the relation of the hot gas to other aspects of galactic dynamics, e.g., the escape of coronal gas from the galactic disk into the halo.

X-Ray Line Emission

Theory predicts that most of the soft X-ray diffuse background radiation arises from emission lines of the elements from carbon to iron. Much will be learned about the composition and physical state of the hot ISM component when these lines are resolved and measured by high-resolution spectroscopy.

Moderate-resolution spectroscopy of the soft X-ray diffuse background was carried out by the Diffuse X-Ray Spectrometer (DXS), a Space Shuttle payload flown in January

1993. This instrument covered about 5 percent of the sky along the Galactic plane, obtaining spectra in the energy range from 0.15 to 0.28 keV with 10-eV energy resolution and a 15° field of view. The spectra recorded by DXS are not equilibrium spectra, which suggests that the local hot ISM may have been heated recently, i.e., within the last few hundred thousand years. Additional observations in other regions of the sky would help to elucidate the recent history of this phase of the local interstellar medium.

Further steps toward capturing the information carried in the forest of emission lines below 1 keV, and in the variations of surface brightness of the soft X-ray diffuse background, will require a high-throughput telescope and detector combination with angular resolution better than 1 arcminute, a spectroscopic capability down to 0.1 keV with an energy resolution of 5 eV or better, and a field of view of several degrees.

2.3.2. Interstellar Dust

As predicted by theory and confirmed by *Einstein* and ROSAT observations, scattering by interstellar dust produces diffuse halos around stellar X-ray images (Figure 15). As much as 20 percent of the X-ray flux from a star near the Galactic center can be scattered into the stellar halo.

It is likely that most of the heavy elements in the ISM are condensed into dust particles whose scattering cross sections, which are a function of wavelength, are enhanced near the absorption edges of those elements. Measurements of the spectra and angular variations of X-ray halos can therefore provide information on the composition, particle-size distribution, particle densities, and spatial distribution of interstellar dust.

In variable sources—especially those exhibiting total X-ray eclipses—the time-dependence of halo properties can also provide information about the distribution of dust along the line of sight and an independent measure of the distance to the source. Moreover, an understanding of the halo phenomenon is essential to the correct interpretation of intrinsically small sources.

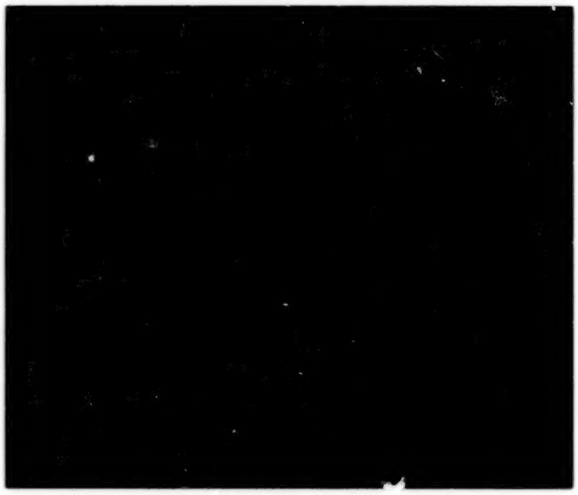


Figure 15. STELLAR X-RAY HALO created by scattering of X-rays from interstellar dust was imaged by ROSAT shortly before and immediately after occultation of the source by the Moon. Post-occultation visibility of halo radiation beyond the Moon's limb confirms the reality of the effect.

Complete measurements of scatter halos, particularly those of variable sources, will require observations of a day or more with an angular resolution of 10 arcseconds or better and sufficient energy resolution to resolve the K-edge absorption features. A start can be made by exploiting some of the longest ROSAT and AXAF observations, but neither mission is likely to offer the protracted observing time necessary to achieve the goals of X-ray halo studies. An instrument for the future would be a high-throughput telescope with an imaging array of detectors that provides an angular resolution of 1 arcsecond, spectroscopic capability down to 0.2 keV with 5 eV energy resolution, and a field of view of 30 arcminutes.

2.4. GALAXIES

In the cases of both normal and so-called "starburst" galaxies, X-rays are produced by stellar sources of the types described above (including both X-ray pulsars and low-mass X-ray binaries), by hot interstellar gas, and by moderate nuclear activity. The distribution and evolution of the stellar X-ray sources can be studied by observing them in a range of different types of galaxies, a program that requires sensitive, high-angular-resolution images capable of detecting individual sources at least as far away as the Virgo cluster. Because X-rays from bright stellar sources are hard, a survey at 2 to 10 keV with modest angular resolution is necessary for their study.

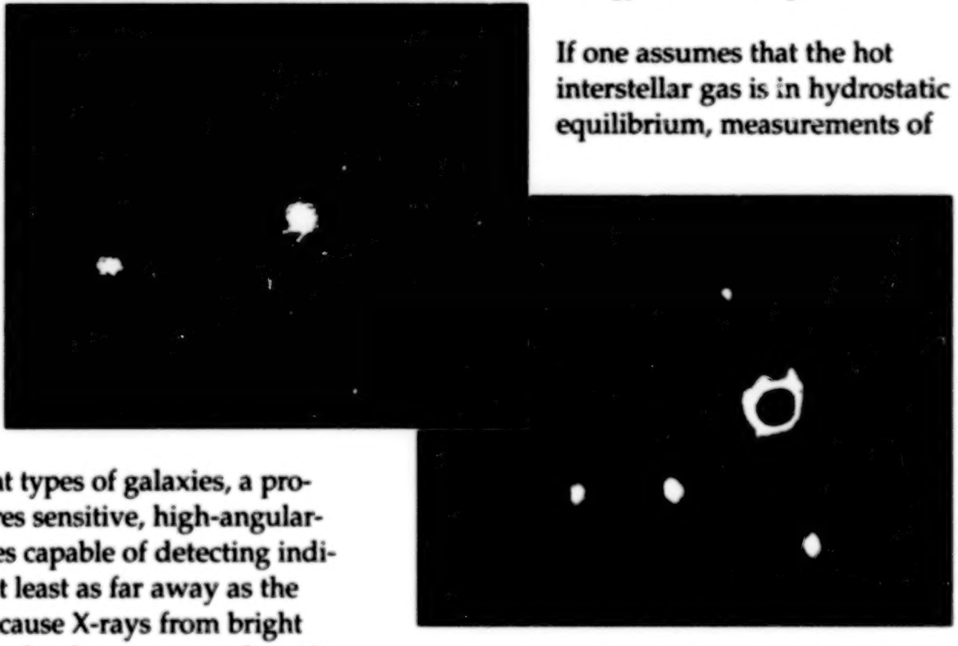


Figure 16. MESSIER 51, THE WHIRLPOOL GALAXY, is actually two interacting galaxies about 10 Mpc away. The nuclear region of the large spiral is unremarkable in a visible-light photograph taken with a ground-based telescope (left), but glows in X-rays in an image recorded by the Einstein observatory (right).

In addition to the X-ray emission produced by stellar sources and interstellar gas, some galaxies with active galactic nuclei (AGN) exhibit powerful X-ray emission from hidden but enormously energetic objects at their centers. These AGN include quasi-stellar objects (quasars), BL Lacertae objects (BL Lacs), and Seyfert galaxies. Because AGN radiate a significant fraction of their total luminosity in the X-ray region, particularly in the hard X-ray region, the energy range from about 1 to 100 keV is crucial for their study.

2.4.1. Normal Galaxies

The characteristic gas temperature associated with the gravitational potential of galaxies is on the order of 1 keV; the dominant, volume-filling component of the interstellar gas would therefore be expected to be a hot, X-ray emitting plasma (Figure 16). This hot interstellar gas—heated by supernovae and other energetic events, cooled by X-radiation, and affected by the inflow of external plasma—holds the key to understanding the energy balance of galaxies.

If one assumes that the hot interstellar gas is in hydrostatic equilibrium, measurements of its X-ray emission can be used to determine galactic masses and to map the distribution of the associated "dark matter." Moreover, because collisions between galaxies will shock-heat gas to high temperatures, X-ray emission from interstellar gas provides a diagnostic for collisions, mergers, tidal interactions, and other environmental effects. The study of the physical and dynamical state of the hot ISM in external galaxies demands observations with high spectral resolution in order to resolve Doppler shifts on the order of 100 km/sec.

2.4.2. Starburst Galaxies

X-ray observations permit searches for newly formed galaxies at high redshift; closer to hand, such observations allow examination of galaxies that are currently undergoing bursts of star formation. In either case, the birth of massive stars leads to a plethora of discrete X-ray sources, including supernova remnants, pulsars, and high-mass X-ray binaries.

The supernova explosions that precede the formation of these objects can shock-heat interstellar gas to X-ray incandescence and drive the hot gas out of the galaxy as a galactic wind. Several nearby starburst galaxies indeed display such X-ray emitting galactic winds, which yield direct information on the rate of mass injection into the intergalactic medium. Observations of hard X-rays at high angular resolution are needed to study the massive stellar component of star-forming systems. Observations of the gas at high spectral resolution are also required.

2.4.3. Galaxies with Active Nuclei

The penetrating power of X-rays makes them one of the best probes of the central AGN power source. The compactness of the regions from which the X-rays emerge is demonstrated by the rapid temporal variability of the observed AGN X-ray intensity.

The high-energy spectra of AGN should provide many clues to the nature of the central source. Although only a few examples have been thoroughly studied, it is already clear that there are several different emission components: a low-energy "thermal" component at (or below) 1 keV; a "nonthermal" power-law component above 1 keV, which extends at least up to 100 keV; a recently discovered "hard" (10 to 50 keV) component, possibly Comptonized emission; and iron emission features near 7 keV. Timing and polarization studies of these emission components should provide us with a clearer picture of the geometry of the source, showing in particular whether the components are produced in the accretion process itself, in an accretion disk, or in other surrounding material.

Spatial and spectral studies of jet phenomena in low-redshift AGN will yield an understanding of the details of particle acceleration and jet collimation. High-resolution imaging and polarization measurements will help to determine the geometry and emission characteristics of the jets in relation to the central source. Besides shedding light on the nature of the AGN power source, detailed studies of the emission characteristics of individual AGN should also lead to an X-ray classification of AGN types. Since all AGN appear to emit X-rays, classifications and catalogs based on X-ray characteristics should be more complete and fundamental than those based on observations in other spectral regions. A clarification of the broad classifications of X-ray and hard X-ray AGN will also be crucial to specifying the contribution of individual AGN to the cosmic X-ray background radiation.

The main spectral-line component of AGN X-ray emission, the 6.4-keV iron line, is a tracer of cold material close to the central engine. An understanding of the mechanism responsible for the iron-line emission will provide detailed information about how the central engine is fed.

2.4.4. X-Ray Surveys of Active Galactic Nuclei

X-ray surveys constitute one of the most powerful techniques for finding AGN of all types. Because AGN have X-ray spectral properties that make them easy to select—and because AGN appear to be the most common type of X-ray source in the sky at low flux levels—sensitive X-ray surveys employing large solid angles detect vast numbers of them. AGN in all known categories are hard X-ray emitters, and there are no selection effects that compromise the construction of complete flux-limited samples of AGN from an X-ray survey.

An appropriate X-ray survey is therefore the method of choice for constructing the data sets necessary to determine AGN evolution, the statistics of beaming, the AGN luminosity function, and the "true" distribution of various AGN types (e.g., Seyfert 1, Seyfert 2, BL Lac, quasar, broad-line radio galaxy), as well as for providing a test of models of the origins of these types.

The median AGN redshift, as detected by flux-limited X-ray surveys with a sensitivity threshold of about 10^{-14} erg cm^{-2} sec^{-1}, is roughly $z = 1.2$, and large numbers of objects are observed out to about $z = 3$. Such surveys can therefore also provide the statistically adequate samples needed to determine the large-scale structure of the Universe on scales of 10 megaparsecs or greater.

The characteristic AGN X-ray luminosity at zero redshift is 10^{43} erg sec^{-1}. In order to determine the evolution of AGN luminosities beyond $z = 1$ directly, without the assumption of any particular functional form for the evolution, a flux-sensitivity threshold of about 3×10^{-15} erg cm^{-2} sec^{-1} is necessary. At this flux level, there are about 500 AGN sources per square degree on the sky; in order to obtain a statistically adequate sample, the survey should therefore cover more than 100 square degrees. Such a survey would also determine the physical correlation function of AGN at a redshift of about $z = 1$.

Observations made by the Japanese *Ginga* satellite have shown that, in most nearby AGN, the equivalent width of the 6.4 keV iron line is roughly 150 eV. An X-ray survey with the appropriate sensitivity and spectral resolution can use this line to determine redshifts and peculiar velocities of AGN and thus yield information on the large-scale velocity field at high redshifts. Comparative studies of starburst galaxies, AGN, and normal galaxies may tell us whether all galaxies pass through an AGN phase during their lifetimes. We may also learn why AGN appear to have been so much more common in the distant past than at the current epoch.

2.5. CLUSTERS OF GALAXIES AND LARGE-SCALE STRUCTURE

Orbiting X-ray observatories have demonstrated that high-energy observations provide a unique capability for the study of large-scale structure, currently a primary focus of astrophysical research. The largest known gravitationally organized systems—clusters of galaxies—are bright in X-rays and have characteristic radii that exceed 250 kiloparsecs. Clusters observed by X-ray telescopes with an angular resolution of several arcseconds therefore appear as extended sources at all redshifts and can be identified unambiguously without recourse to observations in other spectral regions. The study of clusters of galaxies in the X-ray spectral region yields the gas temperature, gas density, and metallicity over the projected volume of the cluster, as well as other astrophysically important information. In addition, measurement of the position of the 6.67-keV iron line in the energy spectrum can provide the cluster redshift.

2.5.1. Cluster Mass Distribution

One of the most fundamental contributions provided by such studies is a determination of the total cluster mass distribution. This is accomplished by combining observations of the temperature and density distributions of the intracluster gas under the assumption of hydrostatic equilibrium—an assumption made plausible by the fact that such equilibrium is readily established in a sound-crossing time, which is nearly 10^9 years (i.e., much less than the Hubble time) for the central regions of a rich cluster.

Such a step in turn permits a comparison of the distribution of the gravitational mass—primarily dark matter—with the distribution of the baryonic material that emits at X-ray and optical wavelengths (Figure 17), thus providing tests of hypotheses of the nature and origin of dark matter. Present studies have been hampered by the lack of spatially resolved spectroscopic measurements, but these deficiencies will be remedied by the next generation of X-ray observatories.

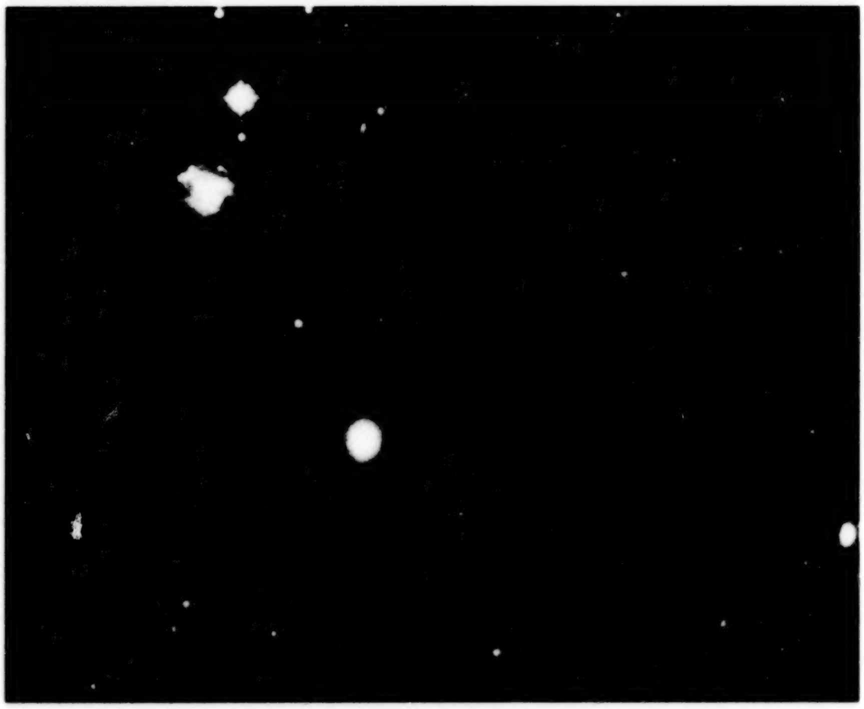


Figure 17. ROSAT IMAGE OF HOT GAS WITHIN THE NGC 2300 GROUP OF GALAXIES is superposed on an optical image of the cluster center.

2.5.2. Heavy-Element Abundances

A second major contribution provided by X-ray observations of galaxy clusters is the measurement of the abundances of heavy elements (notably iron) and their distributions within the cluster. The abundances yield a measure of metal production by the member galaxies over the cluster lifetime, and also provide clues to abundance evolution and the rate of dynamical mass loss. Because of the key role of supernovae in heavy-element production, observations of extragalactic supernova remnants could provide important contributions to such studies.

The study of abundance changes over cosmic timescales can provide information about possible pregalactic generations of stars, the history of star formation, the importance of ram-pressure stripping, and environmental effects on galaxies. Until now, abundance measurements have been limited to nearby clusters and have depended upon instruments with relatively low angular resolution. However, high throughput, together with moderate or high angular resolution, will be required to exploit fully the wealth of information potentially available.

2.5.3. Cosmological Parameters

A third powerful application of X-ray galaxy-cluster observations follows from their combination with measurements of the cosmic microwave background radiation. The microwave-background spectrum is distorted in the direction of a cluster by the inverse-Compton scattering of microwave photons by hot electrons in the intracluster medium—the so-called Sunyaev-Zel'dovich effect. A comparison of the microwave and X-ray observations of a cluster can be used to derive the cluster distance directly, without the need for a redshift measurement. This approach can, in principle, furnish the cosmological parameters H_0 and q_0.

To date, however, X-ray observations have lacked detailed spectroscopy for very distant clusters, and the microwave observations have only recently become free of systematic error. Although the X-ray measurements are difficult and require careful calibration for accurate results, future observations carried out with such telescopes as AXAF nevertheless hold great promise. Moreover, a technique similar to that involving the Sunyaev-Zel'dovich effect—but relying solely on X-ray observations of the cluster and a background quasar—could also be employed; high throughput and high spectral resolution are again required.

2.5.4. Origin of Central Galaxies

A fourth fundamental contribution made by X-ray studies of galaxy clusters is new knowledge about the origin of the exceptionally bright galaxies (cD galaxies) at some cluster centers, a topic that continues to command interest. The two leading formation hypotheses are galactic cannibalism and cooling of the hot intracluster medium. There is growing evidence that cooling of the hot gas is important and that, over the cluster lifetime, this cooling can supply a substantial fraction of the mass of the central galaxies; mass-deposition rates up to nearly 10^3 solar masses per year have been inferred from current observations. However, detailed studies of cooling gas around central galaxies require observations with the highest possible angular and spectral resolution. Although much will be done with AXAF, missions with even higher throughput will also be needed.

2.5.5. X-Ray Surveys of Galaxy Clusters

X-ray surveys of galaxy clusters can provide fundamental new information at all cluster distances (Figure 18). Such surveys provide the only means for obtaining complete samples of gravitationally bound groups and clusters because (a) the X-ray measurements are insensitive to foreground or background contamination, and (b) the clusters are readily identified by their unique, extended-object signatures in the X-ray images.

X-ray surveys will provide samples of clusters whose properties can be directly compared with the predictions of theoretical cosmological models and conjectures, including superconducting cosmic strings, cold dark matter, and massive neutrinos. Studies at a variety of redshifts will provide information about the properties and evolution of density perturbations in the early Universe that we now observe as collapsed objects, bound clusters, and groups of galaxies. Such surveys could be conducted by such observatories as AXAF, but the great demands on observing time required for this work will probably mandate the use of a dedicated telescope whose capabilities are optimized for galaxy-cluster surveys.

2.6. COSMIC X-RAY BACKGROUND RADIATION

The problem of the high-energy (greater than 1 keV) diffuse cosmic X-ray background (CXRB) radiation is the oldest observational puzzle in X-ray astronomy. The discovery of a more or less uniform X-ray glow over the entire sky dates back to the pioneering 1962 rocket flight that first detected Scorpius X-1. After three decades of spectacular progress in X-ray astronomy, the origin of this radiation is still not well understood, although ROSAT observations have begun to provide new insights and to suggest new lines of inquiry.

Because of its relative uniformity—a spatial variation of less than 5 percent on scales of greater than 100 square degrees—it is clear that the CXRB originates at high redshift. The large total flux (it is the major source of cosmic X-ray energy) and hard spectrum make it of particular cosmological interest. There were initially two general explanations or models of the emission: (1) it is made up of numerous weak, unresolved, point-like sources; or (2) the emission is

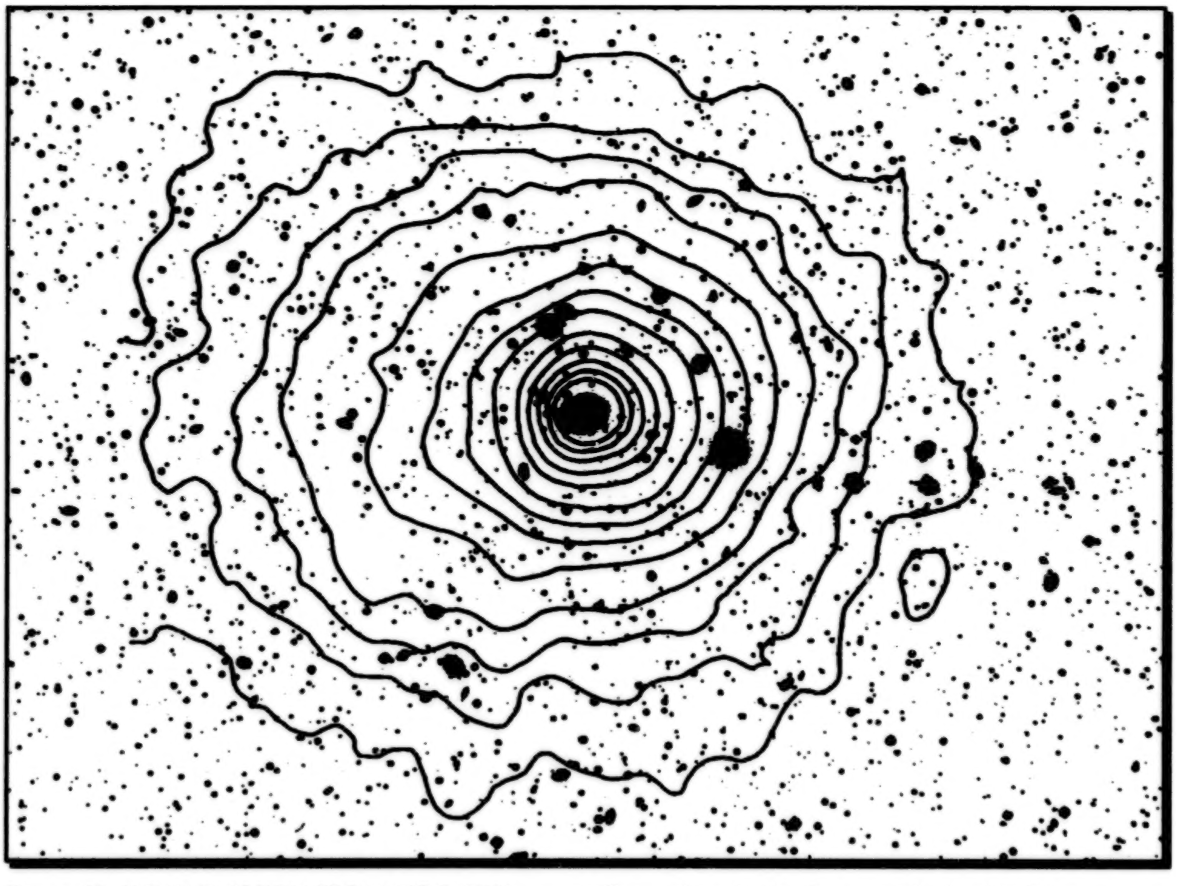


Figure 18. X-RAY EMISSION FROM NGC 1275, an active galaxy in the Perseus cluster (A426), was imaged by the Einstein observatory; the X-ray intensity contours are shown superposed on a Mt. Palomar optical photograph of the cluster. NGC 1275 is the center of a massive cooling flow and also displays strong H-α emission.

truly diffuse on relatively large scales. Combinations of these two models were also proposed.

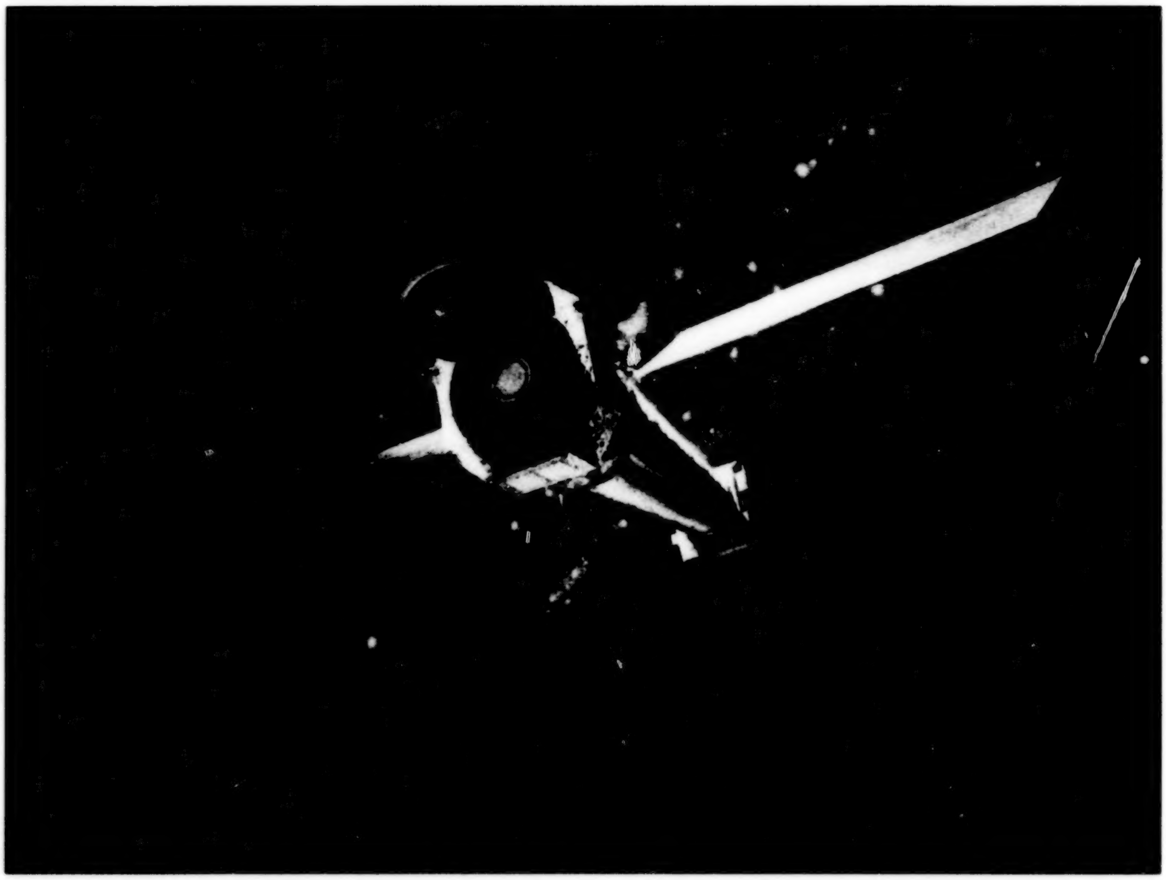
It now appears that the 1-keV CXRB arises mainly from point-like sources; recent ROSAT results show that at least 60 percent of the CXRB at 1 keV breaks up into discrete sources. It is probable that there has been substantial evolution in both the luminosity and spectra of active galaxies at moderate to high redshifts.

However, the spectra of the sources observed by ROSAT have a slope steeper than that of the CXRB, so it is not yet clear how much of the diffuse X-ray flux above 10 keV can be explained by the ROSAT data. A truly diffuse origin on large (greater than 5°) angular scales has been ruled out by recent results from the Cosmic Background Explorer (COBE) satellite, but the diffuse-hot-gas origin could still be tenable on small angular scales. If so, then a substantial fraction (i.e., greater than 1 percent) of the total number of baryons in the Universe was heated to a high temperature at a relatively early cosmic epoch.

Observations by AXAF and XMM should be able to constrain the origin of the CXRB in the band from 1 to 10 keV under a wide variety of hypotheses. It seems quite likely that these two experiments will completely resolve the CXRB (model 1) and place strong limits on any diffuse emission (model 2). However, at a characteristic temperature of 40 keV, the CXRB is a "hard" X-ray phenomenon, so that the AXAF and XMM results will have to be extrapolated to higher energies to account for the observed spectrum. Additional, high-sensitivity measurements in the range from 10 to 100 keV will therefore be required for a full understanding of the CXRB.

The CXRB and the cosmic microwave background are the dominant isotropic radiation fields available for measurement. For the determination of large-scale motions, the X-ray and microwave backgrounds are complementary, since they both define distant reference frames. On the other hand, much of the X-ray background, by contrast to the microwave background, presumably arises from sources at a redshift of less than 10; studies of its surface brightness can thus be used to trace baryons in the "local" Universe.

Measurement of the surface brightness of the X-ray sky on moderate angular scales (in the range from 0.1° to 10°) can determine the tightest constraints available on cosmic density perturbations on spatial-correlation scales from 100 to 1,000 megaparsecs at redshifts less than unity. These data could in turn be used to constrain the existence of such structures as cosmic strings and Zel'dovich "pancakes." At present, however, there are no missions planned to accomplish these goals on large regions of the sky.



ADVANCED X-RAY ASTROPHYSICS FACILITY (AXAF-I), scheduled for launch in 1998, will carry out high-resolution X-ray imaging and spectroscopy of a wide variety of astrophysical objects. This powerful facility will define the forefront of research in high-energy astrophysics and restore NASA's X-ray astronomy program to a position of international leadership.

3

Approved Missions in X-Ray Astronomy

In this chapter, the Working Group discusses approved and operational flight missions in X-ray astronomy under three headings: Advanced X-Ray Astrophysics Facility (AXAF); X-Ray Timing Explorer (XTE); and international missions. The research support and data analysis necessary to maintain the productivity of these missions and the vitality of X-ray astronomy, including the suborbital program, are discussed in Chapter 5. Potential future missions and programs are described in Chapter 6.

3.1. ADVANCED X-RAY ASTROPHYSICS FACILITY (AXAF)

AXAF was selected by the National Academy of Sciences' Astronomy Survey Committee (the Field Committee) as the *number one priority* in all of astronomy for the 1980s. As the more recent Bahcall report has stressed, it remains the most important component of NASA's X-ray astronomy program for the 1990s.

AXAF was originally conceived and planned as a single large mission combining imaging at high spatial resolution with high spectral resolution and excellent sensitivity over the energy range from 0.1 to 10 keV. In 1992, the AXAF project was restructured into two smaller missions: AXAF-I (Imaging), designed for high-resolution imaging and grating spectroscopy, and AXAF-S (Spectroscopy), designed for high-resolution nondispersive spectroscopy. The division of AXAF into AXAF-I and AXAF-S followed a clear and natural separation of scientific objectives and offered a robust, resilient approach to accomplishment of the original scientific goals of the mission. Unfortunately, funding for the development of the AXAF-S telescope and spacecraft was terminated by Congress in 1993 for budgetary reasons.

AXAF-I will provide the astrophysics community with significantly higher spatial and spectral resolution in the X-ray region than has been provided earlier by any NASA or international space observatory, or will be provided by any other planned future mission. As currently configured (Figure 19), the AXAF-I telescope will employ four of the six pairs of grazing-incidence primary mirrors originally specified for AXAF, providing some 700 cm^2 of collecting area at 1.9 keV and about 240 cm^2 at 6.7 keV. The first and largest mirror pair to be fabricated (Figure 20) has been tested at the Marshall Space Flight Center's X-Ray Calibration Facility and found to yield an angular resolution of approximately 0.23 arcsecond—an unprecedented achievement in the figuring of large X-ray primary mirrors. AXAF-I is thus expected to provide spatial resolution commensurate with that obtained by ground-based optical observatories at the most favored sites.

The focal-plane instruments will be the AXAF CCD Imaging Spectrometer (ACIS), which uses charge-coupled device (CCD) detectors, and the High Resolution Camera (HRC), which employs microchannel-plate detectors. Both low-energy and high-energy transmission gratings will be furnished; the ability to measure the iron-line complexes near 6 keV with moderate energy resolution will be retained.

The AXAF-I mission will be launched into a high-Earth orbit either by a Titan-class expendable launch vehicle (ELV) or by the Space Shuttle and a supplementary upper-stage launch vehicle—a feat made possible by the planned use of composite structures to reduce payload weight. Such an orbit also permits simpler systems for power, commu-

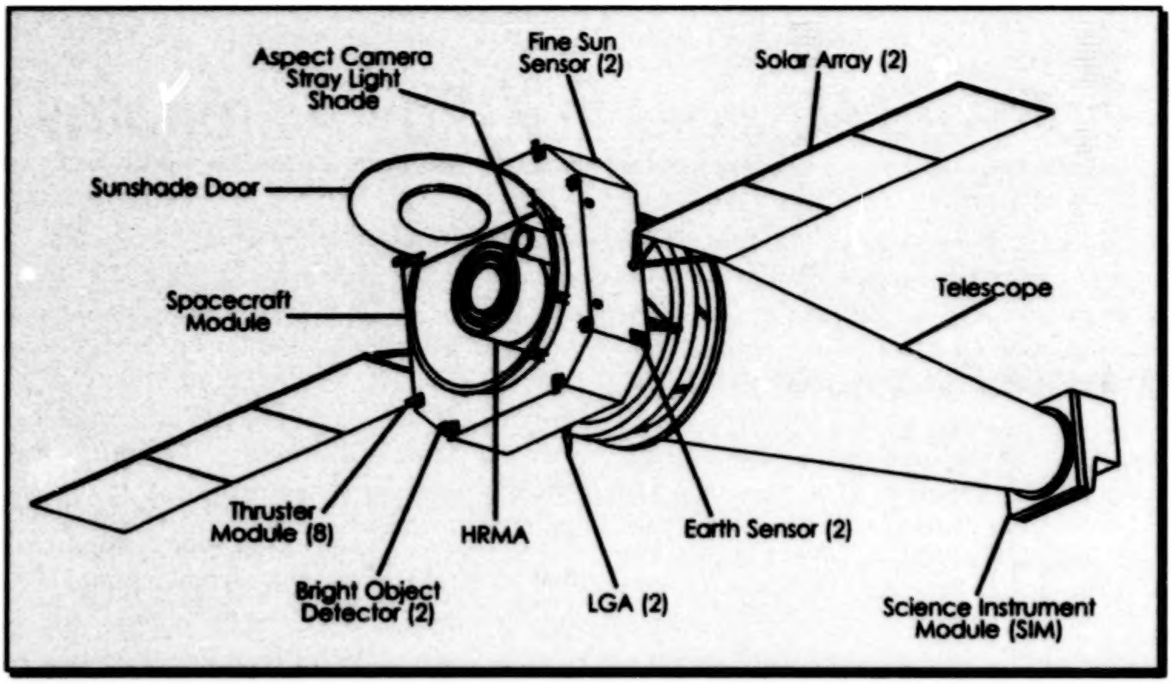


Figure 19. CURRENT AXAF-I CONFIGURATION employs four of the six grazing-incidence primary mirror pairs planned for the original AXAF telescope.

nications, and pointing control. The increased observing efficiency made possible by a high-Earth orbit, together with the fact that only two instruments will share the focal plane, largely offsets the reduction in mirror collecting area.

In terms of high-resolution imaging and dispersive spectroscopy, the AXAF-I mission—with a 5-year baseline lifetime and a likely extension to 10 years or more—is expected to yield an overall level of scientific return comparable to that of the originally planned AXAF observatory. AXAF-I will assure the preeminence of the U.S. role in X-ray astronomy well into the next century. The AXAF Science Center will be important to maximizing the scientific return from this key project.

The cancelled AXAF-S telescope was to have incorporated inexpensive, lightweight mirrors instead of the more accurately figured AXAF-I glass mirror shells. These would have yielded only modest spatial resolution—about 30 arcseconds—but would have been well matched to the sensor-element size of the cryogenically cooled, calorimetric X-Ray Spectrometer (XRS) planned for the focal plane. Now that AXAF-S has been cancelled, it is critical that NASA seek flight opportunities for XRS on another suitable mission.

The scientific rationale that made XRS part of the original AXAF mission (and later the core of AXAF-S) has not changed. In fact, recent spectroscopic results from the Broad Band X-Ray Telescope (BBXRT) and Japan's Advanced Satellite for Cosmology and Astrophysics (ASCA) further strengthen the case for flight of XRS, as they show that an X-ray spectrum rich in emission and/or absorption lines is common to a wide variety of astrophysical objects. Only very high spectral resolution, such as provided by XRS, will permit the routine use of these lines as plasma diagnostics. Moreover, XRS can detect hard X-rays at energies that lie beyond the reach of the AXAF-I gratings—e.g., lines of multiply ionized iron; spectroscopy at these high energies is often essential for the study of sources at temperatures above 10^7 K.

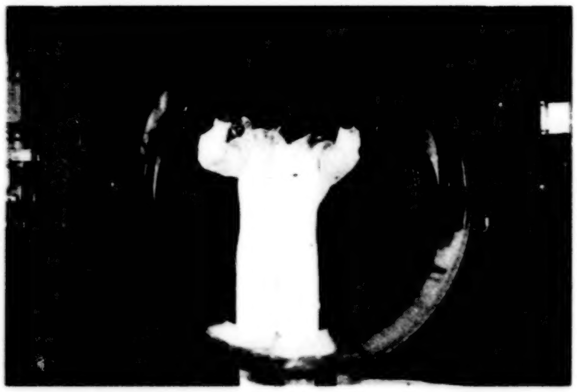


Figure 20. FABRICATION OF THE AXAF-I PRIMARY MIRRORS entails the laborious shaping and polishing of massive glass shells. However, no alternative technique can yet approach the figure accuracy and surface smoothness, essential for high angular resolution, furnished by this established method (see also Figure 1).

It is therefore encouraging that negotiations have already begun with Japan concerning the possibility of including XRS in the proposed ASTRO-E mission. The characteristics planned for the ASTRO-E telescope would appear to be highly favorable to such a match, as discussed in Chapter 6, Section 6.3.1.

3.2. X-RAY TIMING EXPLORER (XTE)

XTE is an ideal example of a modest mission within the Explorer program, one whose completion is long overdue. Originally planned for Shuttle launch and placement on a multi-user Explorer space platform, the XTE mission has now been reconfigured as a dedicated spacecraft launched by a Delta-class ELV. The Working Group supports this step and the establishment of a dedicated XTE Science Center. It is important that resources be provided to permit XTE to be completed and launched on schedule in 1995.

XTE will provide the high throughput needed to study the temporal variability of compact X-ray sources (Figure 21). Its instrument complement includes a Proportional Counter Array (PCA), All-Sky Monitor (ASM), and High Energy X-ray Timing Experiment (HEXTE), which will span the energy range from 2 to 200 keV with a temporal resolution ranging down to 5 µsec.

XTE is the only X-ray experiment planned for the 1990s that covers such a wide bandpass, that probes the shortest temporal regimes, and that can observe virtually the entire sky. These unique characteristics are designed for the study of non-thermal processes near collapsed objects like white dwarfs, neutron stars, and black holes. XTE will probe the structure of matter beyond nuclear densities, the properties of ultra-high magnetic fields, the structure of accretion disks, and the non-thermal properties of AGN.

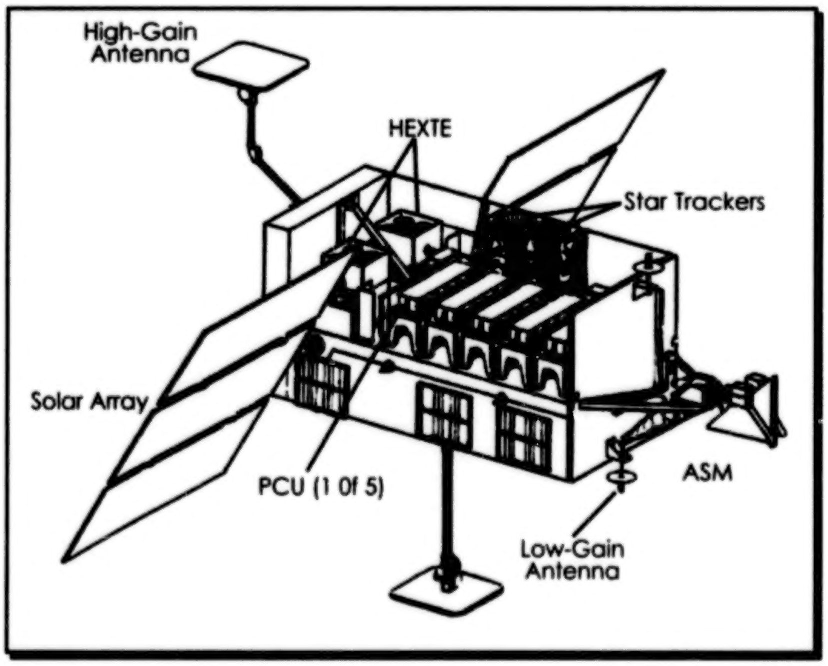


Figure 21. X-RAY TIMING EXPLORER will carry out new observations of X-ray variability associated with collapsed objects, such as white dwarfs, neutron stars, and black holes.

3.3. INTERNATIONAL MISSIONS

Collaborations in international programs have proven to be a cost-effective method for expanding the opportunities of the U.S. X-ray astronomy community for the flight of new instrumentation and the acquisition of new data. In many respects, these international programs for high-energy astrophysics have taken on the role played by the U.S. Explorer program in the 1970s. The highly successful Guest Observer programs on the European Space Agency's EXOSAT mission, the Japanese *Ginga* satellite, and Germany's ROSAT mission have provided the only substantial sources of new data for U.S. scientists since *Einstein* ceased operation in 1981.

The currently operational ROSAT and ASCA missions, which are the main flight missions in X-ray astronomy for the early 1990s, set examples for international cooperation. The Working Group commends NASA for negotiating U.S. participation on three other approved international programs to be launched during this decade: the Argentinian *Satelite de Aplicaciones Cientificas-B* (Scientific Applications Satellite-B, or SAC-B), the Spectrum X-Gamma mission sponsored by Russia and Denmark, and the X-Ray Multimirror Mission (XMM) sponsored by the European Space Agency (ESA).

3.3.1. Roentgen Satellite (ROSAT)

ROSAT, launched by a Delta ELV in June 1990, is a multinational mission led by Germany, with U.K. and U.S. participation. It features a low-energy X-ray telescope with three imaging instruments (one provided by the U.S.), together with an auxiliary wide-field camera for extreme-ultraviolet observations (provided by the U.K.).

During its first 6 months of operation, ROSAT completed an all-sky survey that detected tens of thousands of new X-ray sources and many hundreds of extreme-ultraviolet sources. The mission is now carrying out pointed observations, which are yielding the first new celestial X-ray images since 1981 (Figure 22). The fact that observing time on ROSAT was oversubscribed by a factor of 4 to 5 during the first two years of guest observations underscores the power of this mission for addressing key astrophysical problems.

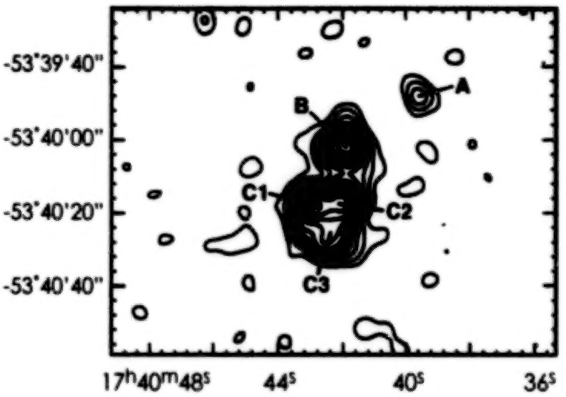


Figure 22. FAINT X-RAY SOURCES GLIMMER FROM THE GLOBULAR CLUSTER NGC 6397, about 2.2 kpc distant, in this deep ROSAT exposure.

3.3.2. Advanced Satellite for Cosmology and Astrophysics (ASCA)

Japan's ASCA mission, known as ASTRO-D before its launch in February 1993, emphasizes moderate-resolution imaging and spectroscopic studies at energies from 0.5 to 12 keV. The United States contributed foil mirrors and CCD-based detectors and will support an active Guest Observer program. ASCA is the first step toward the high-throughput imaging and spectroscopy that is of particular importance for the study of extended sources, such as clusters and supernova remnants (Figure 23), and of quasars, AGN, and other extragalactic sources.

3.3.3. Scientific Applications Satellite-B (SAC-B)

The SAC-B mission, a joint project of Argentina and the United States, is scheduled for launch in 1995 to study solar X-rays, the diffuse X-ray background, and gamma-ray bursts. The diffuse X-ray background investigation, to be carried out with a wide-field CCD detector, will provide the first all-sky mapping of this emission at moderate spectral resolution. SAC-B will be launched together with the High Energy Transient Experiment (HETE) on a Pegasus ELV.

3.3.4. Spectrum X-Gamma

Sponsored by Russia with United States, European, and Danish participation, Spectrum X-Gamma will carry a multiwavelength payload that includes two major U.S. X-ray experiments. The All-Sky X-Ray Monitor (MOXE) is an array of pinhole cameras designed to monitor bright X-ray binaries and transients; the Stellar X-Ray Polarimeter (SXRP) will carry out polarization measurements at energies from 2.6 to 12 keV with sensitivity sufficient to study a variety of sources, such as Galactic X-ray pulsars, black-hole candidates, accretion-disk sources, and several of the brightest AGN. These instruments provide unique observational capabilities that would not otherwise be available to U.S. investigators. Spectrum X-Gamma is planned for a 1995 launch and an operational lifetime of more than two years.

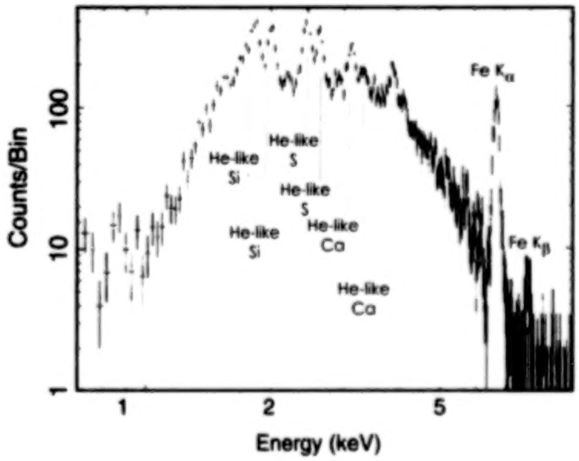


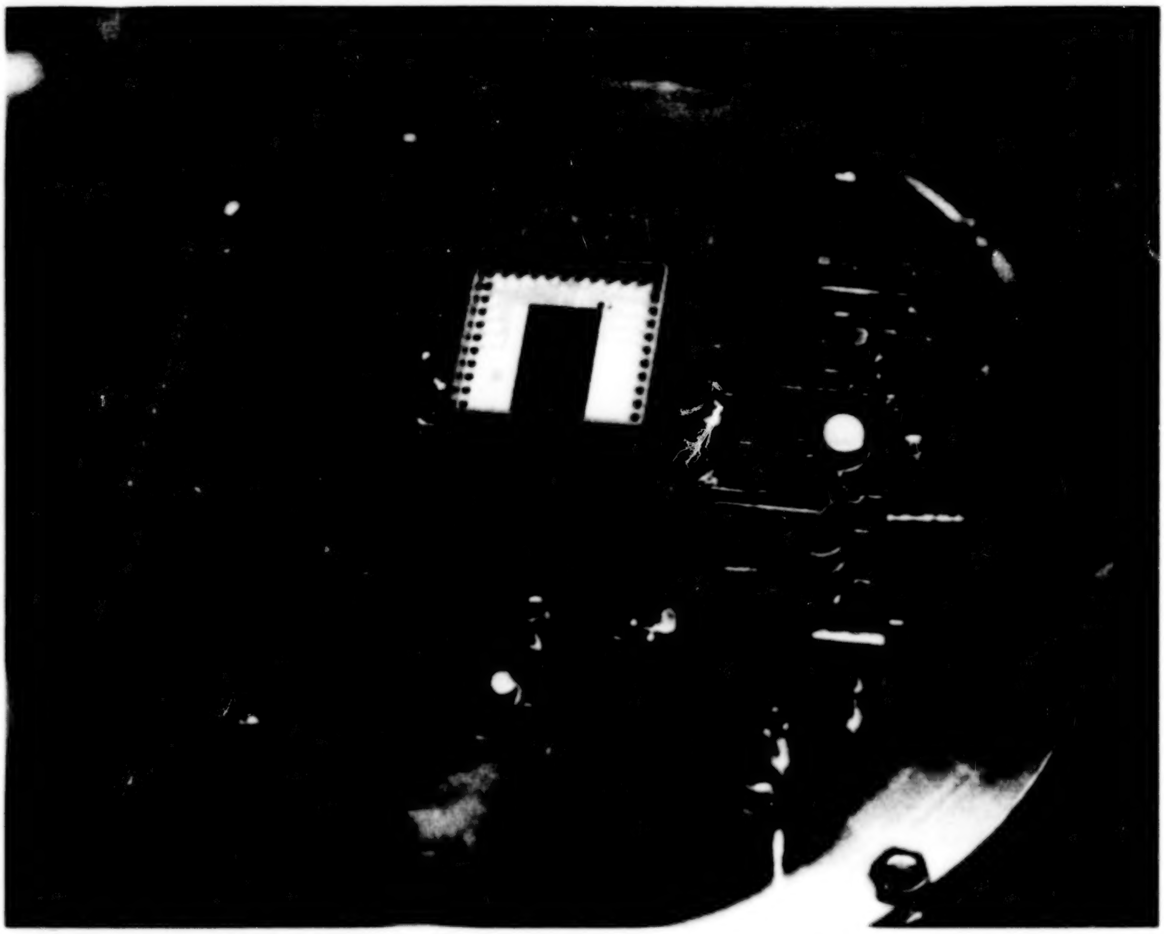
Figure 23. X-RAY SPECTRUM OF THE SUPERNOVA REMNANT W49B demonstrates the high spectral resolution of Japan's ASCA observatory.

A joint agreement between the United States and Denmark grants U.S. investigators a portion of the observing time and data rights from the Danish experiments on Spectrum X-Gamma. In addition, Russia will make available a portion of their observing time, together with all MOXE data, and will release all Russian data from Spectrum X-Gamma to the scientific community within three years.

3.3.5. X-Ray Multimirror Mission (XMM)

Scheduled for launch in 1998, XMM is ESA's cornerstone mission in X-ray astronomy. It will provide high-throughput imaging with 20-arcsecond resolution, together with high-resolution spectroscopy of point sources below about 2 keV. NASA is supporting U.S. contributions to the XMM experiments, including an objective-grating spectrometer and optical monitoring instruments. The first X-ray mirror shells have now been fabricated and the flight instruments selected.

XMM will be complementary to AXAF, providing higher throughput but lower spatial and spectral resolution. These two powerful observatories will operate contemporaneously for many years, giving astronomers the opportunity to optimally exploit the observing capabilities of each on the basis of results obtained with the other.



ARRAY OF CCD DETECTORS FOR THE AXAF-I FOCAL PLANE is shown in this photograph taken during design and testing at Pennsylvania State University.

4 Technology Development

Progress in astronomy flows from the interplay of technology, observation, and theory. Astrophysical theory, for example, is usually pressed forward by the need to explain puzzling or unexpected observations. Advances in observing capability, in turn, are often the result of the application of new technology to astronomy.

Just as Galileo applied the newfound technology of the telescope to change our view of the Solar System and Milky Way, so we today pursue the technologies that will open new windows on the Universe. Through wise investments in technology and their balanced application, the nation can ensure that X-ray astronomy will remain a vibrant research field for decades to come. Although new technologies will certainly be needed, the refinement of more mature technologies is highly important as well. Advances in optics or the fabrication of structures, for example, can dramatically lower the cost of a space mission, permitting an otherwise infeasible engineering task to be carried out.

In this chapter, the Working Group discusses the requirements for both new and refined technologies in the field of X-ray astronomy. These include focusing optics (soft X-rays); indirect imaging (hard X-rays); dispersive optics; detectors; structures; interferometry; and observing platforms and location. The importance of support for technology development through the Astrophysics Division's Supporting Research and Technology (SR&T) program, Advanced Technology Development (ATD) program, and Astro-Tech 21 initiative is stressed in Chapter 5. New and refined technologies essential for the implementation of the next generation of X-ray missions are described in Chapter 6.

4.1. FOCUSING OPTICS (SOFT X-RAYS)

The potential of focusing optics for imaging in the soft X-ray region, powerfully demonstrated by the *Einstein* observator, and again by ROSAT, holds great promise for enhancing X-ray observing capabilities. Over the next decade we can expect to see advances in our ability both to fabricate and to design X-ray focusing optical systems. Two areas command attention: grazing-incidence optics, and normal-incidence optics.

4.1.1. Grazing-Incidence Optics

The current generation of grazing-incidence optical telescopes still relies heavily on the designs for X-ray imaging systems described by Kirkpatrick and Baez in 1948 and Wolter in 1952. However, as our ability to build more capable telescopes increases, so will our ability to achieve more sophisticated designs. The X-ray telescope on the Japanese Solar-A *(Yokoh)* mission, for example, uses a two-hyperboloid system to enlarge the instrument field of view. Field-of-view enlargements by other techniques, such as slight modifications to the more standard Wolter Type I optical design, can greatly increase the capability for the study of large-scale structures on the sky and for the conduct of sky surveys.

Glass Mirrors

The best mirrors carried by cosmic X-ray satellites to date, made of polished glass, have had an angular resolution of 3 to 4 arcseconds. The glass mirrors planned for the AXAF-I (Imaging) mission will achieve a resolution of about 0.5 arcsecond and have lower scatter as well. However, the design goal for the Hubble Space Telescope (HST) was 0.1 arcsecond, and the newly completed Very Long Baseline Array (VLBA) of radio telescopes is capable of milliarcsecond imaging. An increase in X-ray angular resolution to match or exceed that achieved in other spectral bands is a clear goal for the future.

The angular resolution of X-ray mirrors is currently limited by figure imperfections and surface scattering. The figuring of glass mirrors by conventional grinding and polishing remains the preferred method for small numbers of mirrors when mirror mass and collecting area are not primary concerns. New figuring and polishing techniques, including grit-bearing water jets and plasma pucks, now promise to lower costs and improve performance in such cases, although they do not address the concerns of weight or large area. New design approaches—for example, off-plane imaging—may permit scattering problems to be bypassed and resolution to be improved by two or more orders of magnitude; these need to be further investigated through theoretical modeling and laboratory experiments.

Foil Mirrors

Densely nested arrays of reflectors are well suited to applications that demand large collecting area but require only modest angular resolution, such as spectroscopy with solid-state detectors. The main approach to date has been the use of metal-foil cones with shapes that approximate those of the costly, laboriously produced Wolter-type mirrors. Nested mirror arrays of this type, exemplified by the Broad Band X-Ray Telescope (BBXRT) and the Japanese ASCA telescope, have so far achieved an angular resolution of only about 3 arcminutes but support very high throughput up to 10 keV. A refinement of this technique, in which foil-mirror elements are prefigured on a mandrel, offers the possibility of enhanced resolution (about 1 arcminute).

Replicated and Diamond-Turned Mirrors

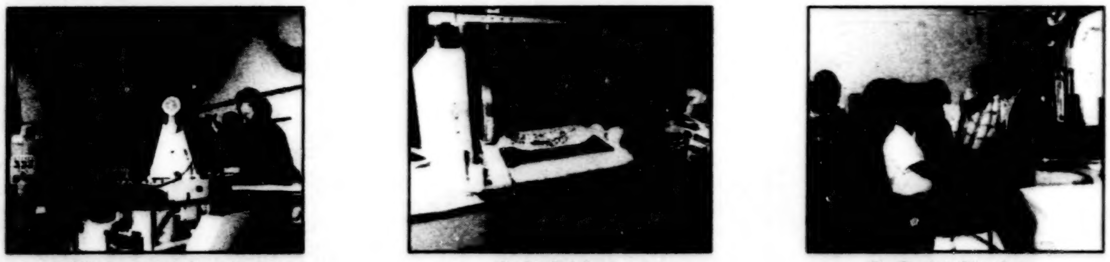
The European X-ray community, by contrast, has invested heavily in a related technology known as replication, which in principle should yield considerably better angular resolution than foil mirrors. In this approach, a mandrel is first constructed to provide a mold of the correct Wolter optical figure; mirror shells are then replicated successively from the mandrel (Figure 24). If many mirrors are to be fabricated, the method also offers substantial economies of scale.

Although replication has so far yielded only modest improvements in resolution by comparison with simple foil cones, future progress could produce a powerful observing tool. The performance of replicated mirrors needs to be demonstrated at the 20- to 30-arcsecond level to show that this approach can provide a practical answer to the need for low-weight, low-cost optics offering modest resolution.

Another technology used for mirror fabrication, employed on NASA's Extreme Ultraviolet Explorer (EUVE) mission, is diamond single-point turning on high-precision, air-bearing spindle lathes using laser interferometric feedback. This technology is capable of 100-Ångstrom precision over a surface of radius 30 cm (which may be extendable to 60 cm) and yields a high-frequency surface roughness of about 10 Å. The excellent performance of the EUVE optics suggests that diamond-turned and subsequently polished mirrors should be capable of arcsecond resolution.

Extension to Higher Energies

The upper end of the energy range to which grazing-incidence optics has been applied is about 10 keV. Although there are important applications to imaging at energies as high as 100 keV, little effort has so far been invested in this area.


1–Diamond Turning 2–Polishing 3–Gold Plating

4–Nickel Shell Polishing 5–Mirror Shell after Separation 6–Testing

Figure 24. STAGES IN THE REPLICATION OF GRAZING-INCIDENCE MIRRORS are schematically illustrated in this sequence of photographs provided by NASA's Marshall Space Flight Center.

It is encouraging that the X-ray reflectivities of gold and iridium have been found acceptable up to energies of 30 to 40 keV. The telescope field of view is small because of the slight grazing angle, and angular resolution is highly sensitive to the mounting tolerances, especially for nested mirrors; nevertheless, these preliminary results are promising enough to warrant consideration of a system with a half-energy width of about 2 arcminutes at such energies. Among the materials that might be used are replicated optics, lacquer-coated foils, float glass, or silicon flats.

For a system optimized at 40 keV, the grazing angle of the outermost mirror shell will be about 10 arcminutes; a mirror with the modest diameter of 9 cm would then have a focal length of some 4 m. However, this geometry assumes that there are only two X-ray reflections between the telescope aperture and focal plane, so that throughput is maximized. Although this has been the case for every grazing-incidence telescope to date, a multi-reflection "folded-optics" telescope is an alternative design possibility. If reflectivity remains good at high energy, the practical advantage of compact size might outweigh the loss in throughput.

The demonstration of acceptable performance with arcminute resolution and significant effective area is a necessary first step in the extension of grazing-incidence optics to high energy. If subarcminute resolution could be achieved, it would be possible to locate hard X-ray sources with sufficient accuracy to identify counterparts in other spectral bands; one could also resolve complex structure, such as that found in the Galactic Center region.

4.1.2. Normal-Incidence Optics

Multilayer optics, formed by the sequential deposition of thin interference films, have already seen astronomical applications. High-resolution X-ray images of the Sun have been obtained from sounding rockets by the Normal Incidence X-Ray Telescope (NIXT), and wide-field imaging of the extreme-ultraviolet sky by similar reflectors was a goal of the Array of Low-Energy X-Ray Imaging Sensors (ALEXIS) experiment.

Multilayers have important capabilities that complement those of grazing-incidence optics. Operating at normal incidence by coherent Bragg reflection, they provide high-resolution images across broad fields of view (10° or more) over the narrow band-pass for which interference is constructive. Multilayers are also relatively inexpensive and can, in principle, yield large effective areas. Because of fundamental problems with surface-layer smoothness, however, they currently work best at wavelengths longward of 30 Å, although this limit may eventually be reduced to 10 Å. By contrast, grazing-incidence optics can be used at higher energies and remain efficient over a very wide energy range.

Improvements or further developments in multilayer technology are needed in the areas of polishing of substrate optical surfaces, deposition of high-reflectivity multilayers of shorter period, and fabrications of larger surface areas. At present, spherical mirrors with diameters up to about 15 cm can be polished to a surface finish of a few Ångstroms; this technique needs to be extended to aspheric surfaces and larger areas. The deposition of high-reflectivity, short-period multilayers demands improved surface finish, but the techniques for deposition of layers only a few atoms thick need development as well.

4.2. INDIRECT IMAGING (HARD X-RAYS)

Grazing-incidence optics are currently applicable below about 15 keV. Although future technology development may produce focusing optics that are effective up to 40 keV, as discussed above, all current systems for imaging hard X-rays in the energy range from 15 to 300 keV use indirect imaging.

Indirect-imaging approaches fall into two categories: (1) simple collimation schemes, and (2) multiplex collimation schemes. Examples of the former are provided by instruments aboard the Japanese *Ginga* satellite and the X-Ray Timing Explorer (XTE); in practice, they are limited to opening angles of about 1°. In multiplex collimation schemes, by contrast, all detector elements view the entire image field; such arrangements yield higher sensitivity, a larger field of view, and relaxed alignment requirements. Coded apertures, modulation collimators, and Fourier-transform techniques all fall into this category. Each of these indirect-imaging approaches encodes the photon signal temporally or spatially on the detectors.

The key technology needs for hard X-ray imaging lie in the areas of lightweight, deployable structures with active stabilization and control, together with the optical systems needed to determine the alignment of multi-grid configurations.

4.2.1. Coded Apertures

A coded-aperture system acts like a multiple-pinhole camera, encoding information about the incoming photons in the form of overlapping images on the detector. Uniformly redundant arrays are one particularly attractive choice for the hole pattern. Coded-aperture techniques have been demonstrated on Spacelab-2 instruments, on a hard X-ray telescope aboard the Russian *Mir* space station, and on balloon-borne hard X-ray detectors developed by U.S. research groups. They have also been studied in connection with proposed high-energy X-ray investigations from the Space Station. In addition to accurate masks and stable structures, detectors with modest spatial resolution are required at the focal plane (see Section 4.4.3). Detectors with submillimeter resolution over the large areas corresponding to mask sizes of 1 x 1 meter will be necessary.

4.2.2. Modulation Collimators

Modulation-collimator systems use two grids, each having parallel linear slits separated by a distance large compared to the slit width. The grids are rotated or rocked to modulate the photon flux as a function of time; detectors with spatial resolution are not required. Rotation-modulation collimators were used for solar imaging by the Japanese *Hinotori* mission, and for the imaging of cosmic sources by NASA's third Small Astronomy Satellite (SAS-3), the British *Ariel-5* mission, and the Japanese *Hakucho* mission. Scanning-modulation collimators have been used for imaging of the Sun by balloon-borne instruments and for the imaging of numerous cosmic sources. Multiple pairs of grids are typically needed in order to sample a wide range of angular scales.

4.2.3. Fourier-Transform Techniques

In Fourier-transform imaging, a photon-encoding scheme provides direct measurements of specific Fourier components of the source distribution. These can then be processed to yield an image of the source, as is done in very-long-baseline radio interferometry. Because the angular resolution depends upon the spatial scales of the collimator masks, and not upon the position resolution of the detectors, angular resolution approaching 1 arcsecond can be achieved. Fourier-transform techniques have been proposed for a multi-pinhole, occulting-disk facility designed to obtain arcsecond images of solar flares and bright cosmic sources in the hard X-ray and gamma-ray spectral regions.

4.3. DISPERSIVE OPTICS

High-resolution spectroscopy is an important and productive area of X-ray astronomy (Figure 25). Although the past decade has produced major advances in the energy resolution of X-ray detectors, these have not yet achieved the resolution needed to extract all the information present in the source spectrum—particularly at long wavelengths, where dispersive optics are at their best. Spectral resolution in excess of 10^4 is needed to reach the next interesting regime for X-ray spectroscopy; this represents approximately an order of magnitude improvement by comparison with present performance.

Dispersive optics include both transmission and reflection gratings. Transmission gratings were used on both *Einstein* and EXOSAT, and they are planned for use on AXAF-I. Reflection gratings, by contrast, are just beginning to find application, most notably on ESA's planned X-Ray Multimirror Mission (XMM). An off-plane mount of the transmission gratings offers a substantial improvement in reflection-grating efficiency and spectral resolution by comparison with in-plane designs, although it requires a very high ruling density. Further work on techniques to control aberrations is also needed; reflection gratings with variable ruling spacing, for example, were specially fabricated for the Extreme Ultraviolet Explorer (EUVE) and will be used on XMM.

Other approaches to the improvement of gratings are also becoming available. In particular, holographic fabrication is now being applied with great success in the ultraviolet and visible spectral regions and should find valuable application at X-ray wavelengths as well.

4.4. DETECTORS

We consider here four categories: charge-coupled devices (CCDs), microchannel plates (MCPs), very low temperature detectors, and hard X-ray detectors.

4.4.1. Charge-Coupled Devices

Charge-coupled devices offer a number of advantages for X-ray imaging. These include

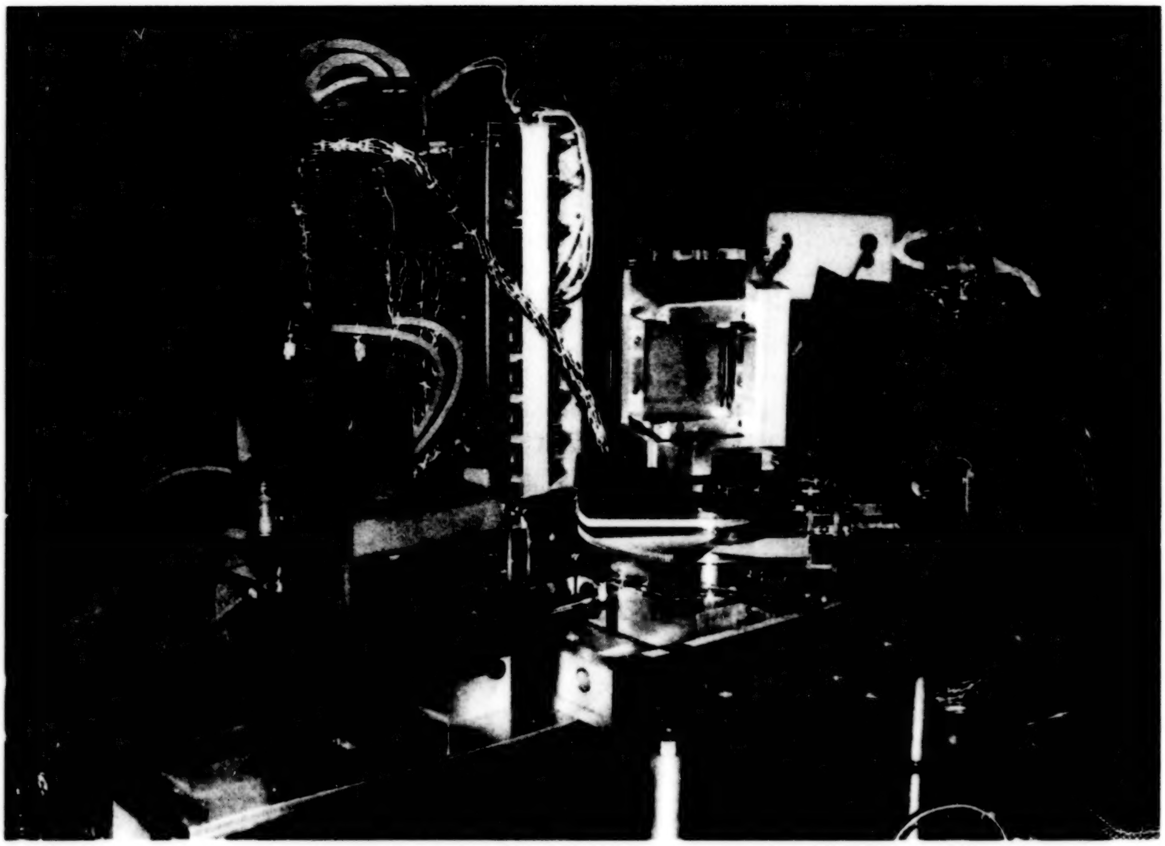


Figure 25. X-RAY SPECTROMETER USED TO EVALUATE CRYSTALS and other diffractors for possible application to X-ray missions was developed by MIT's Center for Space Research. Among parts visible are data-recording and control electronics and the primary detector, an imaging proportional counter.

a well-defined and stable pixel format, good energy resolution, lack of energy dispersion, high quantum efficiency, and nearly complete background rejection. As a result of efforts over the past decade, CCD performance has now reached the theoretical limit in some parameters.

Consider, for example, background rejection. Over typical pixel sizes, which range from 6 to 30 μm for currently available devices, X-rays usually generate single-pixel events, whereas cosmic rays generally cause multi-pixel events. An analysis of the spatial distribution of the event on the detector, together with a consideration of energy thresholds, can therefore be used to reject background events with a confidence of more than 99 percent for optimally designed CCDs.

The energy resolution of CCDs is limited only by the 3.65 eV needed to produce an electron-ion pair and, above 2 keV, by the Fano factor of 0.116. Quantum-detection efficiency, on the other hand, is limited by the gate structure at low energy and by the thickness of the depletion region at high energy. These two factors combine to limit useful efficiency to the energy band between 0.5 and 10 keV. Although current CCDs are nearly ideal detectors over this energy range, it will be important to extend the range to both lower and higher energies, as well as to fabricate large-area arrays and improve radiation hardening.

Extension of Energy Range

Because amplifier noise is low (about 2 eV), CCDs could in principle be built to operate at energies as low as 100 eV and still provide moderate energy resolution. Such an advance would, for example, permit use of CCD instruments with the low-energy objective-grating spectrometer planned for AXAF-I.

Two schemes have been proposed to accomplish such an extension to low energies: (1) creation of an "open" area above the gate structure, which could have an area up to half that of a pixel; and (2) thinning of the CCD back side to within 5 to about 50 µm of the front gates, so that the device can be illuminated from the back. While progress is being made in the production of thin, back-illuminated devices with high and stable efficiencies at low energies, further work is needed to produce a stable surface. At energies above 10 keV, by contrast, devices with greater depletion depth are needed. These could be made on materials of very high resistivity, such as 10^4 ohm-cm silicon, or others, such as germanium.

Large-Area Arrays
CCD detector arrays are also well suited to survey missions, which benefit from large fields of view. Because individual CCDs can be fabricated into mosaics with very little seam loss, the charge-transfer efficiency of many of today's CCDs would permit individual CCD arrays of up to 2,048 pixels on a side without serious degradation of energy resolution. The thinning of such large-format CCDs may allow them to be mounted on curved substrates conforming to the focal surface of a wide-field X-ray camera.

Radiation Hardening
Charge-coupled devices require further development in the area of radiation hardening. Protons from the Earth's radiation belts and from solar flares produce dislocations in the silicon crystal lattice that raise the dark current and lower the charge-transfer efficiency. In a typical low-Earth orbit, radiation damage limits the optimum-performance lifetime of current CCDs to only a few years. In high-Earth orbits, such as that planned for AXAF-I, ambient radiation exposure may rise by a factor of two, and the additional possibility of sporadic, intense solar-flare proton fluxes dictates special shielding.

It may also be possible to reduce CCD sensitivity to radiation damage by changing the way that charge is transferred through each pixel, but further design work and testing must be completed in this area. In all cases, the performance stability of new CCDs must be demonstrated over a long timescale in order to show that they are useful for future missions. Technical advances are thus necessary but not sufficient for future CCD detector applications; systematic CCD testing must be carried out as well.

4.4.2. Microchannel Plates

Microchannel plates (MCPs) have been used for high-resolution imaging in X-ray detectors since the early 1970s. The High Resolution Imager (HRI) on *Einstein* made use of MCPs and an electronic readout to provide a detector that matched the several-arcsecond angular resolution of the X-ray optics, and the currently operating ROSAT observatory incorporates an MCP-based imaging detector of similar design.

The High Resolution Camera (HRC) to be used on AXAF-I will provide a significant stride forward in MCP design and performance. This imaging detector has a 10-cm x 10-cm format with a full-width, half-maximum spatial resolution of better than 25 µm (corresponding to 0.5 arcsecond on the AXAF focal plane), and the MCPs are coated with CsI to improve quantum efficiency over that of a bare-glass surface. Moreover, the HRC will be made with a special glass that is free of radioactive isotopes, so that the background level will be an order of magnitude less than that of previous devices.

Although MCP technology is well established, several areas of improvement are under study. The limiting factor in MCP spatial resolution is the size of the microchannels. Standard MCPs have pore sizes in the range from 10 to 15 µm; MCPs with pore sizes of 5 µm or less are possible, but work is needed to reduce the numbers of cosmetic defects in these smaller-pore devices. MCPs can also be curved to provide a better match to the focal plane of X-ray optics, thereby increasing the useful field of view for high-resolution imaging; however, the electronic readout for MCP detectors will need further development in order to take full advantage of this match. The spectral resolution of current MCP detectors is, at best, limited to broad energy bands ($E/\Delta E$ of roughly unity); however, recent efforts in this area, e.g., with the ROSAT and AXAF detectors, show that further development may lead to improvements in spectral performance.

4.4.3. Very Low Temperature Detectors

Cryogenically cooled detectors for radiation and particles are revolutionizing high-resolution X-ray spectroscopy. Among the most promising such devices at the present time are microcalorimeters operating below 1 K and superconducting tunnel junctions.

Microcalorimeters

Microcalorimeters, which transform X-ray energies into heat, have not only high energy resolution but also inherently high quantum efficiency, which is particularly important for the study of faint X-ray sources. Theoretical calculations suggest that an energy resolution of a few electron volts is ultimately possible, and a resolution of 7.3 eV (at 6 keV) has already been demonstrated in the laboratory. Calorimeter arrays with 36 pixels (3 x 12) have been fabricated, corresponding to a field of view of 1 x 1 arcminute in the focal plane of the cancelled AXAF-S telescope. It should eventually be possible to fabricate even larger arrays (yielding larger fields of view) through the use of superconducting X-ray absorbers, which have essentially no heat capacity.

Superconducting Tunnel Junctions

Superconducting tunnel junctions, which operate at higher temperatures than calorimeters, could in principle yield extremely high energy resolution. Their operation is similar to that of silicon- or germanium-based solid-state detectors. X-rays are converted into charge in a superconductor that has a bandgap energy of only a few milli-electron volts; the charge then tunnels through a thin insulating barrier to a metal contact and is collected by a charge-sensitive amplifier. However, the charge generated per event surpasses that of a conventional solid-state detector by a factor of 10^3, yielding a 30-fold improvement in energy resolution.

It may be possible to construct imaging spectrometers with these devices through use of a suitable detector geometry. Although work is at an early stage of development, an energy resolution of 40 eV at 6 keV has already been achieved, and signal-to-noise considerations suggest that a positional resolution of 5 µm could be attained. Such detectors would represent a significant advance toward the X-ray imaging spectrometers of the future.

The next immediate development goal for superconducting tunnel junctions is an energy resolution of 10 eV at 6 keV. This advance should be followed by the demonstration of an imaging system using such detectors with no degradation of energy resolution.

Other Possibilities

Another X-ray detection scenario is "grain flipping"—the transition of grains out of, and back into, the superconducting state as a result of local heating by X rays. The resulting small changes in magnetic field strength can be detected by superconducting quantum interference devices (SQUIDs) which, in principle, can measure both the energy and position of the X-ray. It is also possible that recently developed high-temperature superconductors may eventually be applied to X-ray detection.

4.4.4. Hard X-Ray Detectors

The next generation of indirect-imaging systems for hard X-rays will require detectors with large area and good spatial resolution, so that faint X-ray sources can be detected and identified. Improved energy resolution will be required as well, both for background rejection and for providing the spectral detail needed to probe the physics of the emission processes. It will therefore be important to demonstrate advances in all of these properties in the laboratory.

The large-area detectors currently capable of millimeter positional resolution at hard X-ray energies include gas proportional counters, gas drift chambers, and liquid-argon or -xenon detectors. Among the most promising candidates for future detector development are high-pressure gas and liquid proportional counters, scintillators, solid-state detectors, and microstrip proportional counters. In addition, good energy resolution might be obtained through advances in bolometer or superconducting-transition detectors; feasibility demonstrations of these technologies should also be attempted.

High-Pressure Gas and Liquids

Gas chambers are typically several centimeters thick and filled with xenon to provide a reasonable interaction cross section for photons with energies up to about 50 keV; somewhat higher energies can be reached with high-pressure systems. Five centimeters of xenon gas at a pressure of one atmosphere has a detection efficiency of about 50 percent and a typical energy resolution of 10 percent at 20 keV. Better resolution (e.g., 5 percent at 20 keV) can be achieved with gas-scintillation or multi-step readout techniques.

High-pressure systems employing 10 cm of xenon at 5 atmospheres are now beginning to attain efficiencies of 50 percent at 100 keV, and fluorescent-gating techniques are being developed to increase the efficiency and lower the background. Further development of gas-system technology, as well as support for feasibility demonstrations of liquid-xenon and argon systems, is desirable.

Scintillators

Inorganic scintillation detectors, which include NaI(Tl), CsI(Na), and CsI(Tl), are attractive for imaging applications that do not demand high spatial resolution. They can provide good photon-detection efficiency (approaching 100 percent at 100 keV) and moderate energy resolution (about 15 percent at 100 keV).

Spatial resolution is typically achieved through the use of (1) discrete detectors to sample the photon distribution, or (2) "scintillation camera" techniques, in which a single scintillation detector is viewed by several photodetectors (e.g., photomultiplier tubes). Typical scintillation cameras can attain spatial resolutions down to 0.5 cm at 100 keV. The key technology need is improvement of the optical readout for large-area scintillation systems. Approaches under study include fiber readout, microchannel plates, and position-sensitive photomultiplier tubes.

Germanium Solid-State Detectors

Good energy resolution (about 1 percent at 100 keV) can be achieved with high-purity germanium detectors. At present, most such detectors are not position-sensitive, but technology development may make germanium matrix or drift detectors practical in the future. The development of position-sensitive, high-resolution germanium detectors should be encouraged, along with such supporting technology as mechanical coolers and inexpensive low-noise amplifiers.

Microstrip Proportional Counters

Microstrip proportional counters offer a promising new avenue for high-energy X-ray detection. In this approach, the usual discrete anode and cathode wires are replaced by conducting strips on an insulating (or partially insulating) substrate. Such devices have been fabricated with anode bars down to 2 µm and on a variety of substrate materials, including thin films that can be molded into a range of shapes. The results achieved to date include 30 µm spatial resolution, high rate capacities, and an energy resolution of better than 11 percent at 5.9 keV.

4.5. STRUCTURES

The evolution of X-ray astronomy requires the development of inexpensive, lightweight, deployable structures to support the long focal lengths of grazing-incidence optical systems and coded apertures. Long structures may also be required for less conventional X-ray facilities, such as Fresnel zone-plate telescopes and interferometers; deployable structures are also needed to obviate unreasonable (and unnecessary) demands on spacecraft length.

4.5.1. Station Keeping

Another way to achieve long X-ray focal lengths is through the conceptually appealing approach of "station keeping," made possible by the photon-counting nature of X-ray detectors. The optics and detectors would be placed on two separated, unattached orbiting structures, with alignment and stability of the "telescope" (true focus, coded aperture, Fresnel zone plates, etc.) with respect to the detectors maintained by the separate spacecrafts.

Post-facto image reconstruction is a standard technique in X-ray astronomy, and station-keeping is in some ways simply an extension of this technique. The feasibility of station-keeping needs to be addressed, together with a comparison of this approach with more traditional methods involving rigid or semi-rigid structures.

4.5.2. Modularity

Certain kinds of investigations require numbers of large, modular structures in space. Instruments of this type have been proposed, for example, for Space Shuttle or Space Station deployment. However, a more broadly ranging study of prospects for modular structures and their uses—whether intended for the Shuttle, the Space Station, free-flying spacecraft, or the Moon—would be beneficial to high-energy astrophysics generally. Apart from launch vehicle and orbit, questions of cost, transportation, assembly, and maintenance would need to be examined. There is clearly a need in X-ray astronomy for facilities of very high throughput, which will ultimately require large structures, perhaps of modular design.

4.6. INTERFEROMETRY

For X-rays, the restriction in angular resolution imposed by diffraction would seem to be slight. At 10 Ångstroms, for example, the diffraction limit for a 1-m mirror is 0.2 milliarcsecond. However, the angular sizes of even the nearest X-ray emitting accretion disks lie in the microarcsecond range. The achievement of angular resolution on this scale requires interferometric techniques that link instruments at large separations.

Because radio astronomy led the way into the milliarcsecond regime, we are today confronted with the paradox that observations carried out at the longest wavelengths provide the images of highest available angular resolution. The proposed Astrometric Interferometry Mission (AIM) may extend milliarcsecond imaging capabilities into the visible and ultraviolet spectral regions. But in the X-ray region, where it would appear to be relatively easy to obtain diffraction-limited images, formidable technical obstacles have prevented a practical beginning. The field of X-ray interferometry remains embryonic.

Although there is currently little effort in this direction, two general approaches appear to offer promise: (1) the creation of grazing-incidence analogues of Michelson interferometers, and (2) the accurate timing of measurements made by widely separated satellites analogous to Hanbury-Twiss interferometers. Both techniques require additional conceptual development followed by laboratory studies. Clearly, other new ideas and techniques in this direction should also be encouraged and supported.

4.7. OBSERVING PLATFORMS AND LOCATION

The choice of observing platform can have a decisive effect on the overall scientific return from an X-ray astronomy mission. Satellite placement in the two basic types of Earth orbit is first discussed, together with the tradeoffs that must be made between these locations. A concluding discussion of alternative platforms and locations emphasizes the importance of free-flying satellites in Earth orbit.

4.7.1. Satellites in Earth Orbit

With NASA's return to the use of expendable launch vehicles (ELVs) as the primary means of launching scientific payloads, satellite placement in high-Earth orbit (HEO) as well as in low-Earth orbit (LEO) can be considered (Figure 26). The tradeoffs between HEO and LEO placement are complex and range from the consideration of the radiation-background environment to the details of mission operations.

Low-Earth Orbit

A pointed satellite in LEO requires a mission-operations approach similar to that of *Einstein*, ROSAT, or HST, in which the observing program is essentially planned in advance and real-time operation is minimal. LEO operation typically yields a viewing efficiency of 30 to 50 percent. If the orbit is high enough, mission lifetime is limited only by the failure of the instruments, but servicing is impossible. Lower orbits permit servicing, as in the case of HST, but the mission lifetime is usually limited by orbital decay unless the satellite is reboosted.

High-Earth Orbit

Placement in HEO suffers from several disadvantages when compared to LEO. In HEO, the ambient radiation background is higher, solar-flare proton fluxes are much higher, a more capable launch vehicle is required, and servicing is precluded. However, these factors are offset by greatly simplified mission operations, the feasibility of extensive real-time interaction, and increased observing efficiency. The high observing efficiencies of EXOSAT and the International Ultraviolet Explorer (IUE), in particular, have provided a dramatic demonstration of these benefits.

Tradeoffs

The choice of orbit depends upon the requirements of the mission. A mission requiring the highest possible sensitivity might best be placed in a circular orbit 300 nautical miles above the Equator in order to realize the lowest possible background. Placement in HEO doubles the observing efficiency but also doubles the ambient radiation background; exposure times may therefore be significantly longer (up to a factor of 4, depending on the type of observation being carried out). Protons from solar flares pose an additional threat.

In the case of photon-limited detection sensitivity, by contrast, exposure time scales linearly, and HEO placement is preferred. The two-instrument AXAF-I (Imaging) spacecraft, for example, will be placed in HEO in order to maximize observing efficiency and compensate for the collecting area lost from the original mission concept. The resulting simplification in communications and mission operations permits substantial weight reduction and therefore the feasibility of launch by an expendable vehicle in the Titan class.

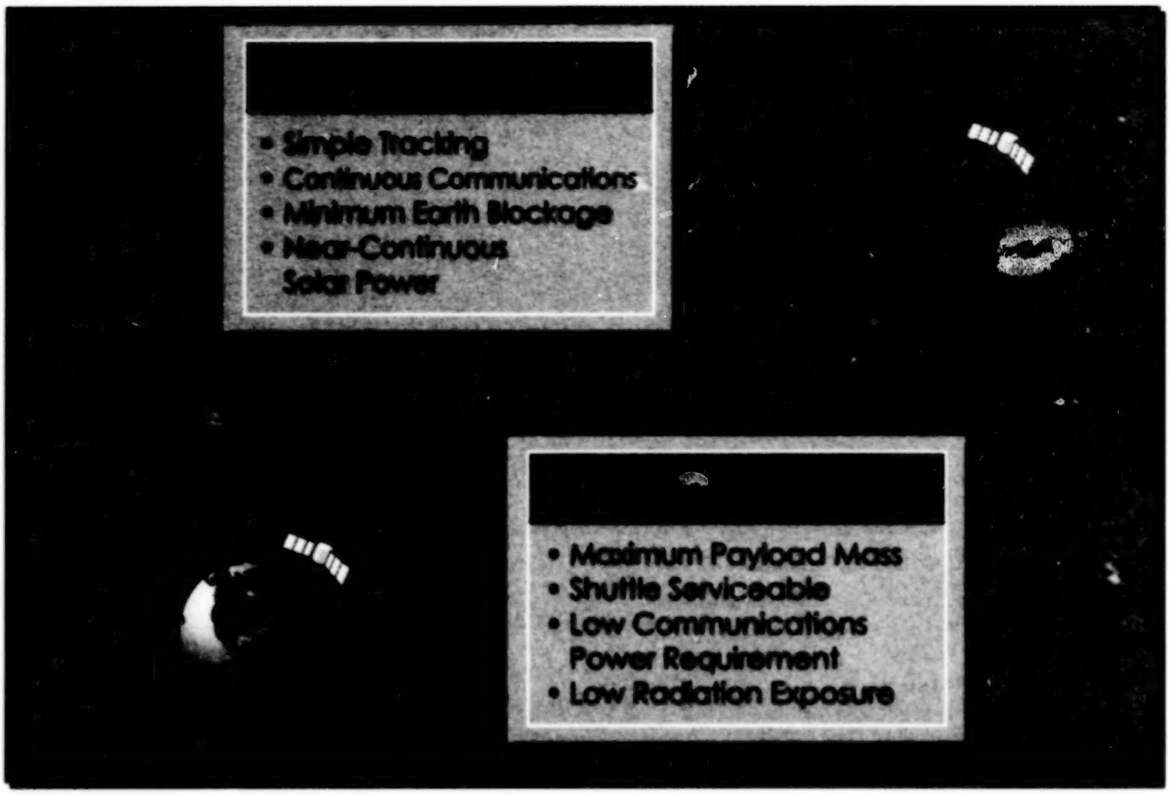


Figure 26. LOW-EARTH AND HIGH-EARTH ORBITS are compared in this schematic diagram, which is not drawn to scale: a typical LEO lies 400 km above the Earth's surface, whereas the nominal HEO for AXAF-I measures 10,000 x 100,000 km.

4.7.2. Alternative Platforms and Locations

Within the X-ray astrophysics community, there is virtually unanimous agreement that dedicated, free-flying spacecraft in LEO or HEO offer by far the most advantageous deployment modes for the great majority of astrophysics missions. The experience of the community in attempting to make use of Space Shuttle flights and projected Space Station observing opportunities for X-ray astronomy has only reinforced this conclusion. Moreover, X-ray observations from the Moon are not likely to be possible within the timeframe of the Working Group plan.

Space Shuttle and Space Station

Despite the clear preference for free-flying satellites in LEO and HEO, alternative platforms and locations could still play a supporting or ancillary role in X-ray astronomy. The Space Shuttle, for example, has provided observing opportunities for several X-ray instruments, including the Broad Band X-Ray Telescope (BBXRT) flown as part of the ASTRO-1 ultraviolet-telescope payload in 1990, and the Diffuse X-Ray Spectrometer (DXS) flown in 1993. Moreover, the flight of U.S. X-ray instruments aboard the German AstroSPAS Shuttle-deployed space platform as part of a proposed "SpectroSPAS" experiment is an attractive possibility.

However, the short duration of Shuttle flights, coupled with the rarity of flight opportunities for any one astronomical discipline, make it unwise to rely upon the Shuttle as a mainstay of the X-ray astronomy research program. For a number of reasons, the Space Station would also be a poor choice as a base for major astrophysical observatories. Both the Space Shuttle and the Space Station should therefore be regarded as platforms of opportunity, rather than as required elements of any long-range plan for the discipline.

The Moon

The Moon may ultimately prove to be the location of choice for those experiments that require long, stable baselines (e.g., interferometers) or that can exploit other aspects of the lunar surface (e.g., radiation shielding). Several such experiments in X-ray astronomy have been identified and should be studied further for possible implementation in the next century. Given the substantial technological and cost obstacles to the establishment of a lunar astrophysics base, however, no strategy for the period 1994-2008 should count on such opportunities in lieu of a series of dedicated, free-flying spacecraft in Earth orbit.

The Einstein Observatory Catalog of IPC X-ray Sources
(FITS Version)
June 1991
Volume 2
08h00m00.0s to 15h59m59.9s
This disk was mastered in ISO 9660 Standard, Level 1. Production of this Catalog was supported by NASA Contract

DISTRIBUTION OF EINSTEIN OBSERVATORY DATA ON CD-ROMs marked the final stage in a lengthy chain of data-handling operations, including acquisition, processing, analysis, and archiving. A mission is not successfully completed until the calibrated and documented data are made accessible to the general scientific community. Einstein photo courtesy of Lotte Jacobi Archives, Instructional Services, University of New Hampshire.

5

Research Support and Data Analysis

A balanced program in X-ray astronomy includes not only flight missions, but also support for the basic research upon which flight programs are built, together with post-flight data analysis and interpretation. This chapter describes the importance of these crucial program elements in six categories: technology development; the suborbital program; laboratory astrophysics; Guest Observer (GO) programs; mission science centers; and archival data analysis and access. Support for these activities is provided primarily through two Astrophysics Division programs: the Research & Analysis (R&A) program, and the Mission Operations and Data Analysis (MO&DA) program. Each is a key part of the infrastructure of X-ray astronomy, and each is essential to NASA's future efforts in this field.

The R&A program encompasses Supporting Research and Technology (SR&T) and Advanced Technology Development (ATD). In the context of X-ray astronomy, the SR&T program supports basic technology development; the design, fabrication, and flight of scientific payloads on sounding rockets and high-altitude balloons; laboratory astrophysics investigations; and theoretical studies keyed to specific X-ray phenomena. Although they represent a modest fraction of the total budget for X-ray astronomy, these R&A programs are critically important for the health of the field. They provide:

- The technology base for future flight missions;
- Support for the basic laboratory and theoretical research crucial to the interpretation and understanding of astrophysical observations; and, most important of all,
- The infrastructure for training the next generation of experimentalists in X-ray astronomy.

The Astrophysics Division's AstroTech 21 initiative is expected to open up an additional avenue for forefront technology development.

The MO&DA program is also a critical element of NASA's Astrophysics program. The scientific return from a flight mission generally continues long after the active flight phase has been completed; the peak years of productivity, as measured by the numbers of papers published in refereed scientific journals, may in some cases occur as much as 5 to 8 years after launch. This time lag is due to the need to adequately understand the performance of the instruments, together with the extended effort required to fully interpret new data and fit them into the body of existing knowledge. The long-term character of this effort underscores the need for stability, continuity, and long-range planning in MO&DA activities. Astrophysics MO&DA supports a wide variety of activities, among them the following:

- Mission operations for current flight missions, carried out in partnership with NASA's Office of Space Communications;
- Science operations for current flight missions, which takes place largely within dedicated mission science centers and includes vital data-handling functions;
- Mission-specific data analysis, funded by grants to Guaranteed Time Observers (GTOs) and Guest Observers (GOs);

- Archival data analysis, funded by grants awarded through the Astrophysics Data Program (ADP), the Long-Term Space Astrophysics (LTSA) program, and the Astrophysics Theory Program (ATP);
- The High Energy Astrophysics Science Archive Research Center (HEASARC);
- Remote access to archival data provided by the Astrophysics Data System (ADS).

All of these MO&DA activities are essential for a healthy science program. However, several merit emphasis because they reach a broad spectrum of the scientific community, attracting researchers with experience in other wavelength bands to the forefront of X-ray astronomy and helping to ensure an optimal scientific return from X-ray missions.

5.1. TECHNOLOGY DEVELOPMENT

The development of new ideas and concepts for detectors, optics, structures, platforms, and other advanced technology is the foundation upon which future missions in X-ray astronomy will be built. A vigorous program of technology development is therefore an essential investment in space science generally and in X-ray astronomy in particular. Future support for Astrophysics technology development will be provided through SR&T, ATD, and AstroTech 21.

The SR&T program will continue to support basic research, including innovative technical approaches to detectors and optics that will be needed for the missions of the next decade and are of a scope that can be addressed by a typical university-sized research group. The ATD program will provide the primary technology-development support for specific planned or approved missions whose technology needs have already been defined. Both ATD and AstroTech 21 will be targeted at forefront efforts that represent the most challenging technology permitted by the state of the art or that exceed the capabilities of the average university-based research group.

5.1.1. SR&T Program

Investment in the SR&T program yields a large payoff in future flight programs, for a significant fraction of the technology used in current flight programs can be traced directly to earlier SR&T support. For example:

- Conical foil-mirror optics—Broad Band X-Ray Telescope (BBXRT), ASCA, and Spectrum X-Gamma
- CCD X-ray imaging—AXAF CCD Imaging Spectrometer (ACIS) on AXAF-I, and ASCA
- High-resolution microchannel-plate imaging:—High Resolution Camera (HRC) on AXAF-I, and ROSAT
- X-ray microcalorimetry—X-Ray Spectrometer (XRS)

X-ray astronomy missions in the next decade will likewise depend directly on technology development undertaken during the current decade. Moreover, technology development supported by SR&T funding provides not only hardware, but also the best training ground for a new generation of space scientists. It is within the SR&T program that payloads are developed and often flight-tested in a space environment on sounding rockets or high-altitude balloons. This experience can provide graduate students with a complete exposure to experiment design, execution, and analysis, and is often directed by a young faculty member or staff scientist.

Investment in technology development is required now to identify state-of-the-art technologies needed to ensure maximum scientific output of these future space missions. However, there has been no real growth in SR&T funding over the past five years. As a result, some critically important and innovative ideas are not being supported. Nor are we able to provide adequate opportunities for students in the areas of technology and instrumentation training. Past constraints in this program have already reduced the ranks of talented space experimenters. It is quite likely that a generation of students has already been lost to the field, greatly reducing its vitality and attractiveness.

The increasing complexity of X-ray astronomy instrumentation and the performance requirements of new detectors has in turn placed an increasing demand upon SR&T support for development. The Working Group strongly urges an increase in SR&T funding for this crucial activity.

5.1.2. ATD Program

By contrast with SR&T, which generally supports basic research in technologies that can be applied to many investigations (e.g., detectors and optics), the ATD program is targeted to support technology needs for specific future missions. There is also a difference in the scope of effort; whereas SR&T normally supports research that can be undertaken by a typical university-sized group, the ATD program is targeted at major, forefront technology-development programs that require more extensive resources, often located at an industrial facility. For example, ATD support permitted the development of several key technologies for the AXAF mission, including the highly accurate grazing-incidence mirrors for AXAF-I and the design of the focal-plane detectors. Clearly, ATD support will be required for the development of technologies for many of the future X-ray missions described in Chapter 6, once the technology needs of those missions have been more rigorously defined.

5.1.3. AstroTech 21

AstroTech 21 is an outgrowth of a mid-1980s study by the National Academy of Sciences' Space Science Board designed to foresee the principal issues that will face space science in the period 1995-2015. In response to the Board's recommendations, the Astrophysics Division conceived the AstroTech 21 initiative in 1989 as a means for identifying the technologies that would be needed for 21st-century missions, and for bringing them to a state of readiness that would permit their infusion into mission development with a minimum of risk. AstroTech 21 was subsequently broadened to incorporate some of the recommendations of the Academy's Astronomy and Astrophysics Survey Committee for the 1990s (the Bahcall Committee).

This ongoing program has two goals: (1) to identify the future technology needs of the Astrophysics program; and (2) to formulate detailed technology plans for the development and demonstration of necessary technologies. Through workshops and meetings, hundreds of experts from NASA field centers, other federal agencies and laboratories, universities, and industry have already participated in AstroTech 21 activities.

Technology plans for four future Astrophysics missions have been produced to date, and a two-volume AstroTech 21 Technology Development Program Plan has been published jointly with NASA's Office of Advanced Concepts and Technology (OACT, formerly the Office of Aeronautics and Space Technology). This plan will be regularly updated and distributed to program managers at NASA Headquarters, to project managers at NASA field centers, and to appropriate personnel in other Federal laboratories, industry, and universities.

Implementation of AstroTech 21 is to be jointly supported by the Astrophysics Division and OACT. It is projected that OACT will provide most of the resources for technology development; the Division's Advanced Programs Branch will carry out mission concept and definition studies, which will determine and refine advanced technology requirements for future missions. When the requisite level of technological maturity has been reached, the Division will assume responsibility for technology development, demonstration, and infusion into project design and development phases.

The Working Group commends the Astrophysics Division for the initiation of AstroTech 21 and urges the further strengthening of this program to permit identification, definition, and demonstration of forefront technology applicable to X-ray astronomy.

5.2. SUBORBITAL PROGRAM

The suborbital program in X-ray astronomy consists of sounding-rocket flights and high-altitude balloon flights. The success of the Supernova 1987A suborbital campaign demonstrates the importance of a rapid-response observing capability and the potential for significant scientific as well as technological return from these programs. The continuation of rocket and balloon programs in X-ray astronomy, with sufficient funding for frequent flight opportunities, is an important element of the overall balanced program advocated by this report.

Moreover, the combination of laboratory technology-development programs with rocket and balloon flights provides a proving ground for innovative technologies, exploratory scientific concepts, and precisely defined scientific objectives. This environment is one of the principal areas of the X-ray astronomy program where the timescale from mission concept to realization can be short enough to be spanned by the typical graduate-student academic lifetime.

5.2.1. Sounding Rockets

Several active groups conduct important research programs using sounding rockets (Figure 27). For example, X-ray imagers flown on rocket payloads from 1990 to 1993 recorded the most detailed images of solar X-ray coronal structure yet obtained using state-of-the-art, multilayer narrow-band filters. Sounding rockets continue to be valuable for studies of the low-energy diffuse X-ray background, supernovae and their remnants, and the testing of such new technology as CCD detectors, advanced grating designs, and polarimeters.

Figure 27. A VIGOROUS SOUNDING-ROCKET PROGRAM is essential for the development and testing of X-ray instruments that will later be used on orbiting satellites.

Sounding rockets are also of particular importance for student training. A graduate student can carry out a complete sounding-rocket research project, beginning with system design and ending with analysis of data from the flight. The long development times typical of orbital missions makes such a complete involvement by students impossible. Moreover, orbital flights require large front-end investments, which discourage risk-taking and therefore also diminish opportunities for student participation in the total spectrum of mission development.

The minimal time required to prepare a sounding rocket for flight is another important advantage. This program responsiveness facilitates the study of important transient events, such as nearby supernova explosions, when no other observatories are available to carry out the observation.

5.2.2. High-Altitude Balloons

In the 1990s, new balloon technology promises to increase observing opportunities in the hard X-ray band above 30 keV. High-altitude balloons can now remain aloft for two weeks or more, permitting longer exposures than the Space Shuttle. Several groups are now active in using these platforms for important observations in the hard X-ray band. Moreover, as in the case of sounding rockets, such experiments also make possible the pursuit of innovative ideas, the economical testing of new detector technology, the training of students, and a rapid response to transient events.

5.3. LABORATORY ASTROPHYSICS

The accuracy with which physical conditions in astrophysical sources can be inferred from spectroscopic observations depends directly on the breadth and precision of data available for atomic processes. The laboratory research that yields these data must be supported to ensure that the maximum scientific insight can be extracted from observational data at X-ray wavelengths. Thus, laboratory astrophysics research complements theory and observation in the interpretation of astrophysical phenomena.

Of particular importance to X-ray astronomy are studies of the highly ionized atoms relevant to X-ray spectroscopic observations. Diagnostics of high-temperature plasmas such as the emission from highly ionized iron are relevant to the study of numerous astrophysical sources, including galaxy clusters, supernova remnants, accretion sources, and stellar coronae. With the enhanced spectral resolution provided by ASCA and expected from AXAF and XMM, detailed understanding of such diagnostics will become increasingly important. The Working Group therefore urges enhanced support for laboratory astrophysics.

5.4. GUEST OBSERVER PROGRAMS

Grants provided to Guest Observers (GOs) are among the most popular and productive means for broadening access to spacecraft observations and data, and for carrying out initial data analyses. The first announcement of GO opportunities for ROSAT, for example, was greeted by more than 700 proposals for the first 6 months of general observations—a five-fold oversubscription. This level of interest has persisted through the first two years of the ROSAT Guest Observer program. The GO program for mission-specific observations and data analysis is therefore an important supplement to MO&DA support for Guaranteed Time Observers (GTOs), who consist typically of the Principal Investigators and members of their teams.

By drawing upon the ideas and abilities of a broad spectrum of the scientific community, these GO grants help to optimize the scientific observing program of the mission. Moreover, they provide channels for data access and dissemination by supporting the analysis of data by the GOs themselves, so that high-level data products can be made available to an even broader community spectrum. The Working Group urges the continuation of vigorous GO programs for currently active missions, and for XTE and AXAF in the future.

5.5. MISSION SCIENCE CENTERS

Support of mission science centers within the MO&DA program provides for a variety of important services, including science planning, hardware and on-line services for guest use, data-processing software, and a wide range of data-analysis software. As a result, mission science centers have been invaluable in focusing the core scientific program of the mission, optimizing the mission observing schedule, consolidating mission data, and disseminating core data products to the scientific community.

The *Einstein* science center was among the first to demonstrate the great value of mission science centers for space astronomy. The outstanding performances of science centers for more recent Astrophysics missions, such as the Infrared Astronomical Satellite (IRAS) and the Extreme Ultraviolet Explorer (EUVE), have confirmed the wisdom of this approach. Science centers also play key roles in establishing long-term mission data archives and in transferring them to more general archival facilities.

The Working Group urges maintenance of MO&DA support for mission science centers in X-ray astronomy, particularly those planned for XTE and AXAF. Such support should be maintained until the consolidated data holdings of the science center are ready for transfer to more general, long-term archival facilities, such as the High Energy Astrophysics Science Archive Research Center (HEASARC).

5.6. ARCHIVAL DATA ANALYSIS AND ACCESS

The Astrophysics Data Program (ADP) and Long-Term Space Astrophysics (LTSA) program were instituted to support data analysis beyond that carried out by the Guaranteed Time Observers (GTOs) and Guest Observers (GOs), which is tied to specific missions. Together with the Astrophysics Theory Program (ATP), these more general archival research programs have been very successful in meeting the needs of the scientific community. Moreover, they make interdisciplinary and multi-wavelength analyses possible, thus ushering in the era of "panchromatic" astrophysics (Figure 28).

The Working Group believes that these grants for archival research should be continued and extended to include the data from new missions as they become publicly available. A policy that would gradually move data-analysis support from the mission-specific GTO and GO grants into the more general ADP, LTSA, and ATP grants for archival research would provide a mechanism for keeping the field healthy and productive. All of these MO&DA functions are essential to optimizing the scientific return from flight missions and to the widest possible data dissemination.

5.6.1. Astrophysics Data Program

The Astrophysics Data Program (ADP) is the primary vehicle for the general support of archival Astrophysics data analyses by individual research scientists. This program supports not only data analysis itself, but also the software development and purchase of computer workstations that can be prerequisites for productive research—particularly for investigators at smaller institutions. The Working Group believes it imperative that support for this pivotal program be continued at a vigorous level.

ADP grants are typically awarded for the analysis of data that have been acquired within the previous few years, usually with the aim of clarifying or explaining specific observations. Although these grants are flexible and permit investigations of the data from multiple missions and wavelength bands, they are currently restricted to proposals utilizing current data sets. The Working Group believes that the ADP selection criteria should be changed to allow new observational data as part of the proposed effort.

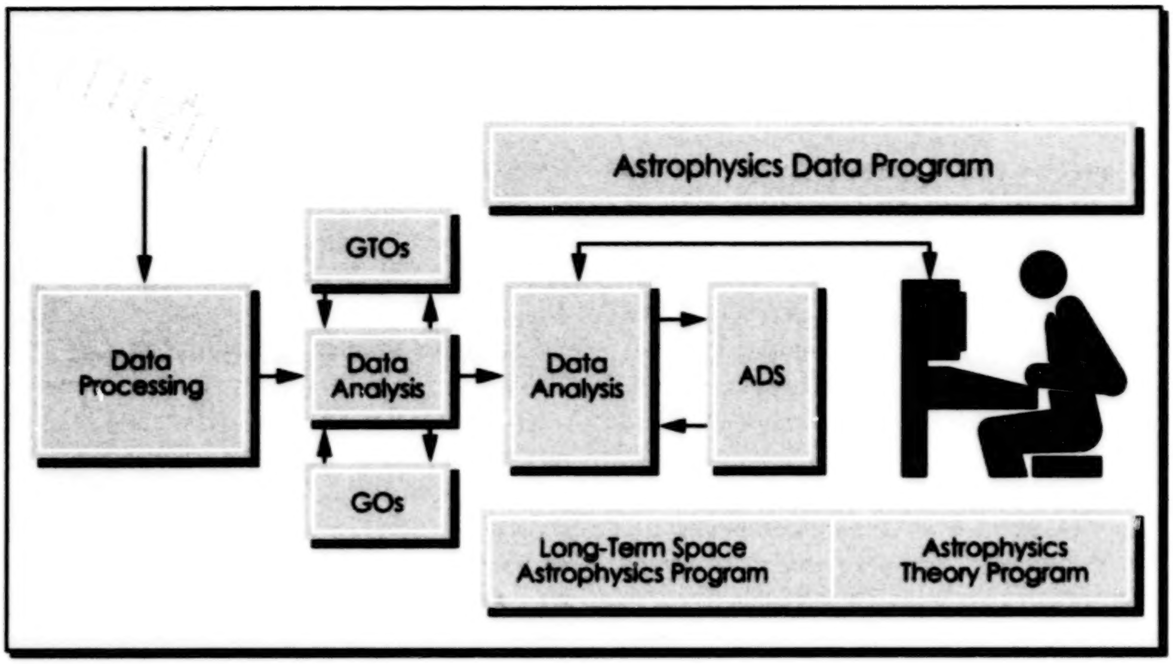

Astrophysics Data Program
GTOs
Data Processing
Data Analysis
Data Analysis
ADS
GOs
Long-Term Space Astrophysics Program
Astrophysics Theory Program

Figure 28. ARCHIVAL ACCESS TO SPACE-ASTROPHYSICS DATA is essential for the study of cosmic objects across the breadth of the electromagnetic spectrum. This research is supported by the Astrophysics Data Program, the Long-Term Space Astrophysics Program, and the Astrophysics Theory Program.

5.6.2. Long-Term Space Astrophysics Program

By contrast with the near-term focus of ADP, the Long-Term Space Astrophysics (LTSA) program is intended to encourage the systematic examination of fundamental scientific problems through multi-year research projects covering theory, modeling, archival and correlative analyses, and infrastructure enhancements. Key features are the science-driven character of the program and the enhanced productivity arising from the long terms of the projects. Furthermore, the LTSA program provides another step in a logical progression of data-analysis support begun with GO and ADP grants.

The LTSA program was initiated through a series of multi-year grants designed to provide stability and continuity to such efforts. Unfortunately, this good beginning has now been threatened by MO&DA funding cuts that have forced the suspension of the 1993 grant announcement. The Working Group urges the speedy resumption of new grants within this important long-term program.

5.6.3. Astrophysics Theory Program

The impact of X-ray astronomy depends on placing X-ray observations into the overall context of astrophysics through theoretical interpretations. Observation and theory work together to provide the fundamental insights necessary for understanding. This is particularly true for X-ray astronomy, where the complex nature of the astrophysical systems (e.g. compact objects, active galactic nuclei) require a broad range of astrophysical theory for the proper understanding of the relevant physical processes.

As in the case of laboratory astrophysics, theoretical astrophysics supplies information on atoms, nuclei, and bulk-matter properties needed for interpreting X-ray images and spectra. However, the extreme physical conditions that typify most X-ray emitting objects often cannot be duplicated in the laboratory; in such cases, only theoretical calculations can supply the necessary ancillary information. In addition, theoretical models are needed to integrate observational data sets and provide a framework for interpretation. Moreover, questions raised by theoretical analyses often help to define the observational requirements for future X-ray astronomy missions, such as the spectral resolution required to detect line broadening or the particular energies at which emission lines are likely to be useful as plasma diagnostics.

A modest amount of theoretical work relevant to X-ray astronomy was supported in the past by SR&T grants awarded by the Astrophysics Division's High Energy Astrophysics Branch. However, these theory grants have been restricted to studies of high-energy processes and were tied closely to specific mission objectives; in any case, SR&T funding is inadequate in itself to support the interpretation of data from X-ray missions generally.

A significant fraction of the theoretical work needed for X-ray data analysis and interpretation is supported through the Astrophysics Theory Program (ATP). The Working Group urges the maintenance of strong support for this program, which has proven highly cost-effective in advancing X-ray astronomy to its present level of maturity.

5.6.4. Astrophysics Data System

The Astrophysics Data System (ADS) was initiated to provide rapid, direct, and economical access to archival data from Astrophysics missions. In an era of multidisciplinary studies, it is essential that the scientific researcher have convenient and uniform access to relevant and current data regardless of where these data happen to be stored. The Working Group supports the continued operation and further development of ADS and urges the inclusion of additional data archives and data services within it.

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Pegasus
Brigadeiro Montenegro

PEGASUS EXPENDABLE LAUNCH VEHICLE developed by Orbital Sciences Corporation exemplifies the type of low-cost launcher that will be used for future NASA Small Explorer (SMEX) missions. The vehicle is carried aloft by a modified L-1011 aircraft, dropped from a high altitude, and then commanded to begin the payload launch.

6

Future Missions in X-Ray Astronomy

In this chapter, the Working Group discusses potential future programs and flight missions in four categories: a new X-ray "Observer" mission series; Explorer missions; international missions; and a new observatory-class mission to follow the Advanced X-Ray Astrophysics Facility (AXAF). As successors to the approved missions described in Chapter 3, these future missions are needed to address many of the key scientific questions in X-ray astronomy discussed in Chapter 2.

6.1. A New X-Ray "Observer" Mission Series

The launch of AXAF-I in 1998 will be a milestone for X-ray astronomy and will establish important new observing capabilities. However, observing time on AXAF-I is certain to be heavily oversubscribed. Moreover, a number of important astrophysical problems demand observations that cannot be carried out efficiently, or carried out at all, by this facility.

While some of these problems can be addressed by future Explorer missions (see below), many can only be studied by more substantial X-ray observatories in the Delta launch-vehicle class; these would require funding of $100 to $300 million in FY 1993 dollars and about 5 years of development from concept to launch. The Working Group has tentatively given the name "Observer" to this new mission series, which could be phased into the program late in the decade as development costs for AXAF decline. Among the many promising candidates for X-ray "Observers" are the following (this list carries no implication of priority):

6.1.1. High-Energy Imaging between 20 and 200 keV

Except for high-altitude balloon flights, the current X-ray program leaves imaging studies in the hard X-ray region (20 to 200 keV) largely unexplored. It is in this portion of the spectrum that the extragalactic X-ray background has its maximum curvature; the spectra of AGN would reveal whether they are responsible for the cosmic X-ray background. Comptonized emission components of the accretion disks around the central engines of AGN may also emit in this region. A hard X-ray imaging mission is needed to explore the high-energy X-ray regime with sufficient effective area and angular resolution to detect representative samples of all classes of X-ray emitters, and not merely the brightest members of each class. It could combine the functions of a survey, obtain crude spectral measurements, and detect hard X-ray variability in AGN.

The mission objectives include a study of the high-energy spectra of X-ray binaries and AGN, as well as cyclotron features in pulsars. These observations would provide crucial input to the determination of the origin of the hard X-ray background. This mission requires a spectral resolution E/ΔE of about 10 and would need to have a throughput sufficient to detect sources with a flux of 1 percent of NGC 4151 (Figure 29) at 100 keV.

6.1.2. Very-High-Resolution Spectroscopy

A very-high-resolution spectroscopy mission would include a spectrograph with a resolving power of 30,000 or so as a design goal, so that the fine structure of atomic lines in the X-ray region could be observed and the line shapes measured. Studies of celestial X-

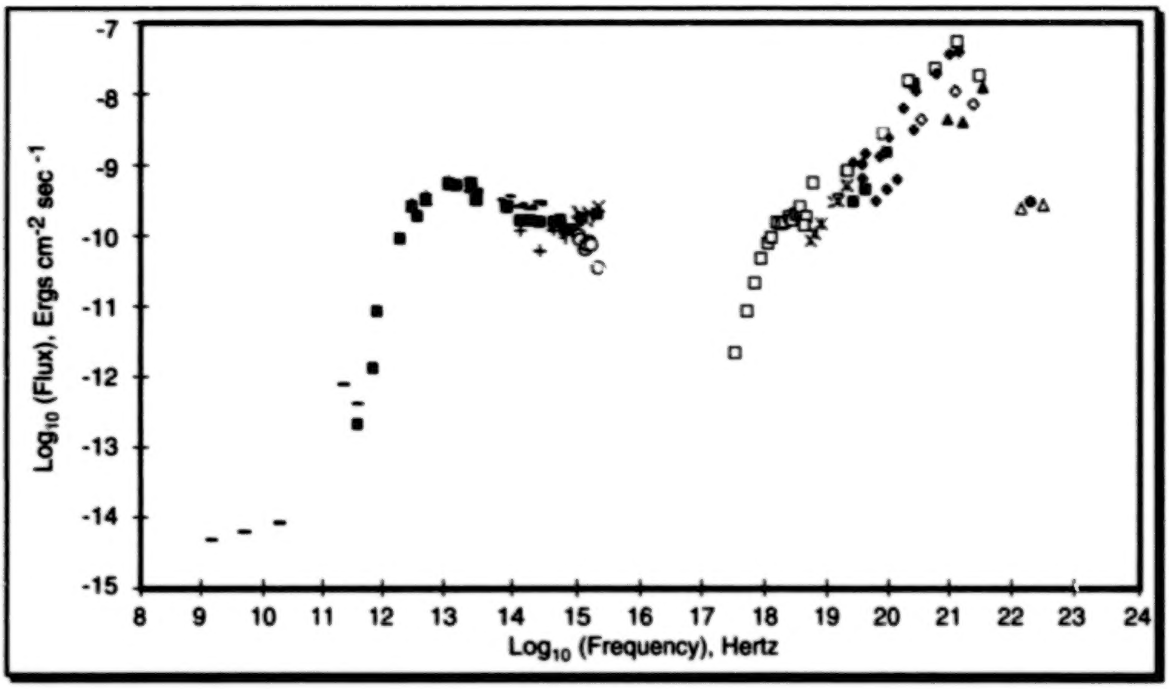


Figure 29. SPECTRUM OF THE ACTIVE GALAXY NGC 4151 from radio to gamma-ray wavelengths illustrates the importance of space observations, particularly in the high-energy band, to the study of active galactic nuclei and many other cosmic objects.

ray sources at this resolution would permit detailed exploration of the physics of all classes of sources. For example, temperatures could be measured from the broadening of individual lines, Doppler shifts could be measured to study binary orbits, and gas motions could be observed in stellar coronae. The attainment of very high resolving power using reflection gratings and grazing-incidence optics will require technological innovations in fabrication and structures.

6.1.3. Grazing-Incidence Imaging up to 40 keV

A high-energy grazing-incidence imaging mission covering energies up to 40 keV could carry out high-sensitivity observations in the portion of the X-ray spectral band where nonthermal emission mechanisms begin to dominate thermal processes. Even moderate angular resolution would yield improvements in the signal-to-noise ratio sufficient for detailed spectroscopic studies of large samples of AGN and Galactic X-ray binaries. The new technology of materials that are efficient reflectors at these high energies would be a driver for this mission.

6.1.4. High-Throughput Spectroscopy

High throughput is crucial for carrying out detailed, broadband spectroscopic observations of faint sources and for time-resolved spectroscopy of brighter sources. This capability is required, for example, for definitive studies of the elemental abundances in intracluster gas in distant galaxy clusters. The need for a high-throughput spectroscopy mission has been recognized in many previous studies of the field. One well-known example of such a mission is the Large Area Modular Array of Reflectors (LAMAR), originally proposed for Space Shuttle flight and later for Space Station deployment, but not yet developed.

6.1.5. An All-Sky Survey from 2 to 10 keV

One of the deficiencies of the approved X-ray program is the lack of a hard or moderate-energy X-ray survey. The survey completed by HEAO-1 was limited by source confusion to flux values only 50 percent lower than those of the original *Uhuru* survey; AXAF-I will be sensitive to moderately hard X-rays with energies up to 10 keV, but it will not be useful as a survey instrument. Now that ROSAT has completed an all-sky survey at lower energies, however, it will be important to have a corresponding arcminute view of the sky in the spectral band from 2 to 10 keV. Because all AGN appear to radiate at moderate and hard X-ray energies, a survey at these energies is likely to be important to an understanding of AGN classification, distribution, and evolution.

An all-sky survey mission from 2 to 10 keV should be able to reach flux levels comparable to those detected by ROSAT in a six-month to one-year survey, so that a collecting area of at least 300 cm^2 over a large field of view will be needed. The survey should have an energy resolution of approximately 100 eV, so that the 6-keV iron line can be used to estimate redshifts for detected AGN and galaxies. The telescope might also be used in a pointed mode to make more sensitive observations. All classes of X-ray emitters would be studied.

6.2. EXPLORER MISSIONS

NASA's Explorer program, administered by the OSS Astrophysics Division but serving the OSS Space Physics Division as well, has produced a sequence of outstanding scientific missions. These have ranged from Explorer-1, which discovered the Van Allen radiation belts around the Earth in 1958, to the more recent triumphs of IRAS, COBE, and EUVE.

Over the past 15 years, however, the Explorer launch rate has fallen to a fraction of its earlier value. The Working Group therefore strongly supports the recommendations of both the Field and Bahcall reports that the Explorer program be returned to a healthy flight frequency, so that the number of Astrophysics Explorers can be increased. Here, the Working Group discusses the recent history of the Explorer program and provides examples of candidates for future X-ray missions within the restructured program.

6.2.1. The Explorer Program

During the 1980s, NASA emphasized larger Explorers, such as IRAS and COBE, typically launched by highly capable ELVs in the Delta class (although some, like EUVE and XTE, were originally planned for Space Shuttle launch). Small-scale missions like *Uhuru* and SAS-3, which largely laid the foundation for X-ray astronomy, have been missing from the discipline for more than a decade.

NASA sought to remedy this deficiency in 1988 by creating a separate Small Explorer (SMEX) mission class. Development cost was restricted to $30 million and payload mass to 500 kg. The initial 1988 SMEX Announcement of Opportunity (AO) resulted in the selection of three such missions, although no X-ray experiment was among them. (A second SMEX AO was issued in 1993, but again no X-ray experiment was selected.)

In 1991, NASA announced that Delta-class Explorers, such as XTE, would be discontinued after the flight of the Far Ultraviolet Spectroscopic Explorer (FUSE) at the end of the decade. NASA then created two more new Explorer mission classes to bracket the SMEX class: the smaller University Explorer (UNEX) class and the larger Middle-Range Explorer (MIDEX) class.

The Working Group believes that these are all steps in the right direction. Such missions generally target specific scientific problems with innovative instrumentation. They can and should be accomplished on rapid timescales in response to newly reordered scientific priorities and promising new technologies. They invigorate and revitalize the discipline, encourage scientific and technical diversity, and provide room for the intimate involvement of young investigators in all aspects of a mission.

However, the SMEX program needs to be significantly augmented so that at least one flight opportunity per year in Astrophysics can be provided. The new UNEX and MIDEX classes should also be funded at a level that affords a reasonable flight frequency for X-ray astronomy missions.

6.2.2. Candidates for Future Missions

The Working Group identified a number of high-priority scientific questions that can be addressed through future Explorer missions. Four candidate missions, representative of many outstanding observing opportunities, are described here to illustrate the promise of future Explorers for investigations in X-ray astronomy (this list carries no implication of priority):

Wide-Field Survey from 0.1 to 2 keV
An X-ray wide-field survey mission (an "X-ray Schmidt" telescope) would cover the band from 0.1 to 2 keV with a large field of view and a moderate angular resolution of about 2 arcseconds. With this capability, deep surveys could be carried out and the candidate optical counterparts to X-ray sources identified unambiguously. Such a mission could also search for distant clusters of galaxies efficiently over several hundred square degrees using the extent of X-ray emission to uniquely identify cluster sources. Both the deep surveys and the cluster surveys would detect large numbers of AGN, which could be used as a flux-limited sample. Such a mission would require new technology in the optical design, focal-plane detector, and in the use of deployable structures.

All-Sky Spectroscopic Survey of the Soft X-Ray Diffuse Background
Observations carried out by Germany's Roentgen Satellite (ROSAT) have now provided a wealth of new detail on the spatial variability of the soft X-ray diffuse background radiation below 1.5 keV (Figure 30). However, ROSAT spectral resolution is inadequate to distinguish between contributions to this radiation arising from Galactic thermal emission, on the one hand, and extragalactic sources, on the other. Because the Galactic component of the soft X-ray diffuse background is believed to consist almost entirely of collisionally excited lines of highly ionized elements, high-resolution spectroscopy is needed to further our understanding of the hot (10^6 K) components of the interstellar medium (ISM). This hot gas, which can only be studied directly through its soft X-ray emission, may play the dominant role in ISM energy balance and evolution.

An all-sky survey of the soft X-ray diffuse background in the energy range from 0.1 to 1 keV with an energy resolution of 10 eV or less would provide an important and unique probe of the hot ISM gas. The observations would also provide new constraints on the evolution of the sources responsible for the cosmic component of the diffuse X-ray background. In view of the spatially detailed ROSAT study in this energy range, an angular resolution of 10° would be adequate for the purposes of this survey.

All-Sky Temporal Monitoring
Active galactic nuclei are believed to be powered by accretion onto a compact object; they should therefore display observable X-ray variability. Because of their high penetrating power, hard X-rays may be able to escape from the innermost regions of the central engine. These small inner regions, which are the ones of greatest interest, are also expected to exhibit the most rapid temporal variability. Because it will be difficult to obtain sufficient observing time on a general facility

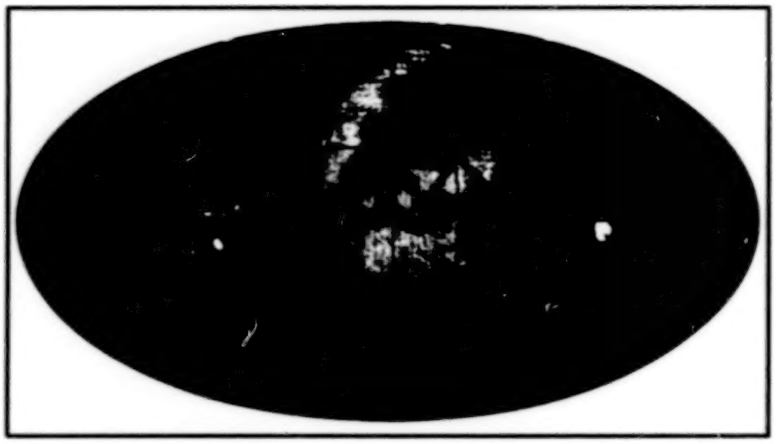


Figure 30. ROSAT SURVEY OF SOFT X-RAY DIFFUSE BACKGROUND was completed during the first months following launch of the satellite in 1990. A survey of this emission at much higher energy resolution (10 eV or less) is now needed to determine its origin.

to study the variations of substantial numbers of AGN in any detail, a dedicated monitoring instrument will be needed.

An all-sky temporal monitoring mission should have a sensitivity sufficient to detect variability in many sources on timescales from about 10^5 seconds (which is near the presently observed characteristic timescale of AGN in the X-ray band) to timescales of less than 100 seconds (the light travel time across the Schwarzschild radius of a compact object of a few million solar masses). AGN variations on even shorter time scales might also be detectable. Such a mission would also provide the capability to detect transients, such as the "breakout" radiation from a supernova in a nearby (Virgo cluster) galaxy. The technological approach to an all-sky survey mission is well understood; the challenge will be to make the program low-cost and to use novel operational approaches to provide high temporal resolution for the study of transient phenomena.

Nebular Spectroscopy

A high-throughput X-ray spectrometer with high spectral resolution is needed to determine the physical state and dynamics of the hot gas in galaxies. High resolution spectra of the 6-keV iron lines from AGN may allow a direct measurement of the motions of the accreting material near the central engine.

A nebular spectroscopy mission should have a spectral resolution $E/\Delta E$ on the order of 1,000 or greater with a collecting area of about 1 m^2 at photon energies of 6 keV. The angular resolution should be about 10 arcseconds. Observations of extended objects, such as supernova remnants, the interstellar medium, and the intracluster medium, could be made in order to investigate the chemistry and physical state of the hot gas in these systems.

6.3. INTERNATIONAL MISSIONS

Given the high benefit-to-cost ratio of international collaborations and the lack of any new U.S. moderate-scale missions for high-energy astrophysics in the 1990s, the Working Group believes that NASA should continue to seek opportunities for such joint projects, provided that they do not adversely impact Research and Analysis (R&A) activities or the Explorer program. Participation should therefore be sought on the proposed Japanese ASTRO-E mission. In addition, there are attractive opportunities to fly U.S. X-ray experiments on Germany's Shuttle-borne AstroSPAS platform, such as the "SpectroSPAS" mission. Data exchanges with other nations are vital to the continued health of the discipline and should be supported as well.

6.3.1. ASTRO-E

The proposed ASTRO-E satellite is the next in the series of highly successful Japanese high-energy astrophysics missions. Both *Ginga* (formerly ASTRO-C) and ASCA (formerly ASTRO-D) have emphasized international collaboration. ASTRO-E has now received approval for development and is in the process of being defined; it is certain to be at the cutting edge of astrophysical research in the late 1990s. Given the growth in U.S.-Japanese collaborations, an exciting opportunity exists for a joint mission.

In particular, the X-Ray Spectrometer (XRS), specified for the original AXAF mission and later slated for AXAF-S, would appear to be an excellent choice of detector for the ASTRO-E focal plane. The combination of ASTRO-E with XRS would produce an enormous gain in sensitivity by comparison with any similar past mission—e.g., a factor of 10^4 or more above that of *Einstein*—and for many figures of merit would exceed by a factor of 5 or 6 even the sensitivity projected for AXAF-S. No other current or planned X-ray experiments will challenge XRS capabilities because they have all been designed with complementary characteristics.

Moreover, the flight of XRS on ASTRO-E would provide the U.S. scientific community with the rewards of a successful and particularly challenging technology-development program. In addition to its contributions to X-ray astronomy, this program has already strengthened national infrastructure in several areas of cryogenics and solid-state detectors. Other spinoffs of XRS technology, particularly in the areas of lightweight, long-lived dewars, may also be anticipated, to the benefit of space astronomy generally.

6.3.2. SpectroSPAS

The Shuttle-deployed AstroSPAS platform, developed by Germany, can support the flight of a new-technology grazing-incidence telescope/spectrograph that would provide high-quality X-ray spectra of a wide variety of astronomical objects. The Working Group strongly supports pursuit of this and other opportunities to place U.S. X-ray instruments on AstroSPAS to conduct a SpectroSPAS mission.

6.4. The Next Observatory-Class Mission

Missions in the facility or observatory class, embodying powerful observing capabilities and extended mission lifetimes, are needed to attack problems at the forefront of research. These are the missions that will have the greatest scientific impact, involve the largest community of investigators and students, enjoy the broadest support from the astronomical community at large, and capture most completely the public imagination.

These missions typically require the most capable launch vehicles available, such as the Space Shuttle or an expendable launch vehicle (ELV) in the Titan or Atlas class. The time interval from concept to launch is 10 years or longer, and overall costs are $1 billion or more in FY 1993 dollars. If such missions achieve long and productive observing lifetimes, they can also be highly cost-effective. There is currently only one such project that has been approved for X-ray astronomy: AXAF-I, scheduled for launch in 1998.

Advanced planning should begin now for an AXAF follow-on mission for flight in the post-AXAF era. Although the Working Group has not attempted to specify its characteristics precisely, it seems clear that such a mission would require high angular resolution (about 1 arcsecond or less), very high throughput (a collecting area of 1 m^2 or more), and advanced focal-plane instrumentation in the areas of imaging, spectroscopy, and polarimetry.

6.4.1. Advanced Mission Concepts

While it is premature to make specific recommendations, advanced planning for any such mission should initially consider two complementary approaches. These concepts require the development of enabling and supporting technologies in the areas of optics, detectors, structures, and launch vehicles. The scientific drivers which determine the selection of one of these or other future observatory-class missions could depend critically on the results from currently scheduled or future missions.

The first approach would consider energies below about 40 keV, so that grazing-incidence optics could be used, and explore the possibility of achieving very high throughput by means of large collecting areas. Such a Very High Throughput Facility (VHTF), which would be a direct AXAF successor for observations up to 40 keV, would meet the need for high-resolution timing studies and high-resolution spectroscopy. The Working Group would propose a collecting area of at least 1 m^2 as a preliminary design goal; however, this might well be a modular mission built up over time to achieve effective areas of tens of square meters. To make full use of the high throughput, a spatial resolution of approximately 1 arcsecond at 1 keV will be required.

The second approach would consider hard X-ray energies above 40 keV, for which grazing-incidence optics are infeasible, and explore the possibility of imaging at high spatial resolution. Such a Hard X-Ray Imaging Facility (HXIF) would provide arcminute imaging in the hard X-ray band with high effective area. It would provide a follow-up mission to XTE with a tenfold greater sensitivity for energies from 20 to 200 keV and extending into the 1-MeV region. This type of mission requires developing high-energy detector technologies (e.g., imaging germanium detectors) and refining imaging techniques to improve resolution and throughput.

6.4.2. Enabling Technologies

Although the mission concepts discussed above are projects for the next century, the new technologies required to implement these and other advanced concepts must be developed during this decade. A technology initiative is needed in three general areas: high-throughput optics, detectors, and high-resolution optics. This development would be in addition to support furnished under the SR&T and ATD programs and might be provided through the AstroTech 21 program, which is aimed at establishing the research and development base for future missions.

High-Throughput Optics

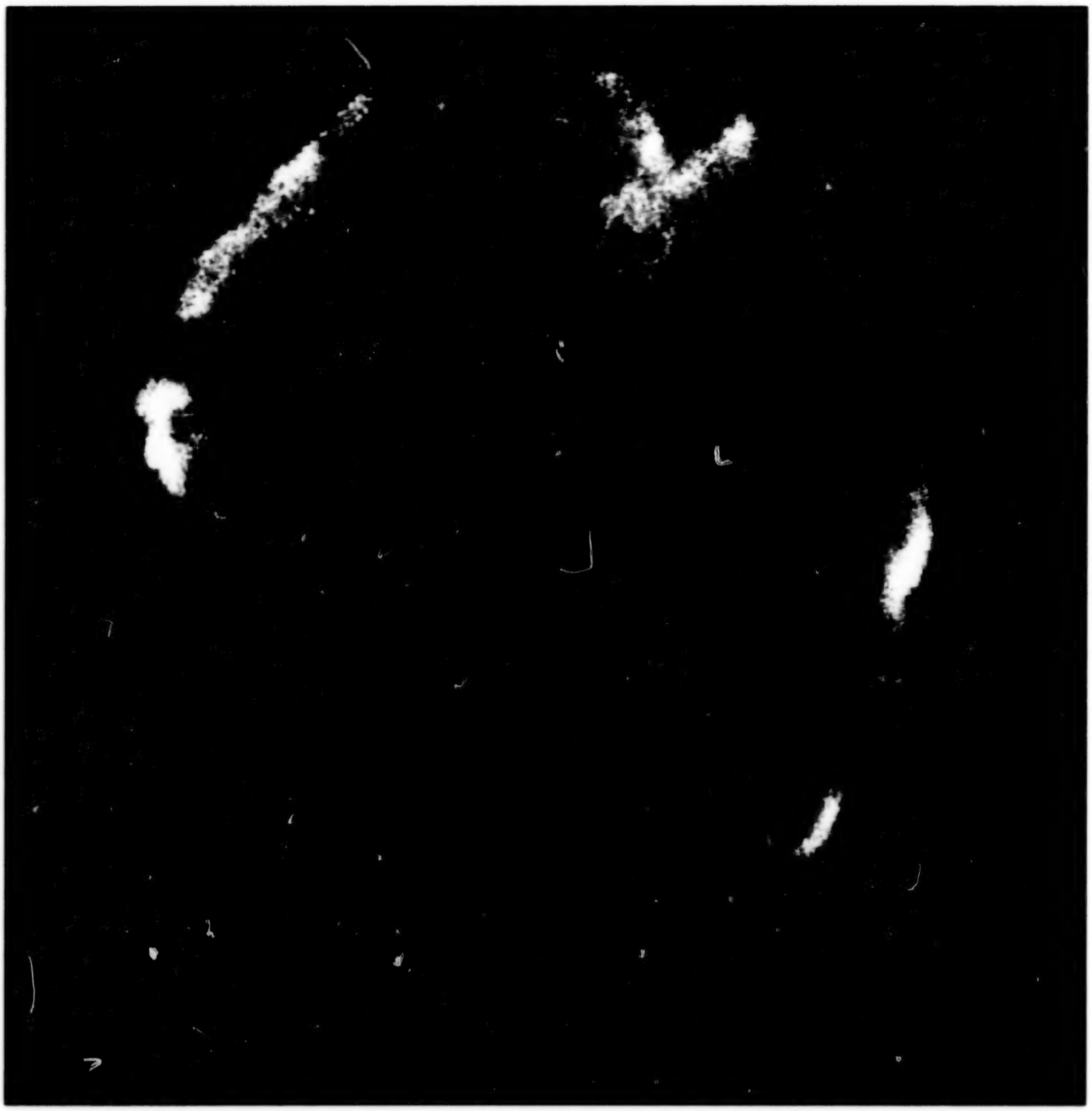
The manufacture of high-quality, low-weight X-ray optics that can be packed into the aperture of a telescope with high efficiency needs to be addressed. Basic studies of mirrors, mounting and assembly techniques, replication processes, and surface finish are needed to achieve the goals of many large missions. The technology for mirrors that maintain reflectivity at energies up to 40 keV should also be investigated.

Detector Technology

Emphasis should be placed on low-temperature detectors in order to achieve high spatial and spectral resolution, including the cryogenic technology necessary to obtain and maintain the detector operating environment. In addition, the development of highly efficient objective-grating spectrometers with very high spectral resolution will be needed to support high-throughput missions. At hard X-ray energies, large-area position-sensitive detectors with good energy resolution will be needed as well.

High-Resolution Optics

The next order-of-magnitude step in X-ray optics will be subarcsecond telescopes, with the goal of achieving milliarcsecond resolution while maintaining good surface finish and large collecting area. Such instruments will approach the limits of resolution attainable with direct-imaging optical systems. The next major subsequent advance will involve interferometry. The technology will include fabrication of such optics, together with the structures needed to mount and fly them. Large structures will also be needed for future hard X-ray imaging systems. Auxiliary technologies, such as measurement, alignment, and calibration, will also be required.



SHOCK-HEATED INTERSTELLAR GAS CLOUDS in the constellation Cygnus are detailed in this ROSAT soft X-ray image. The "Cygnus Loop" was shaped by shock waves from a supernova detonation some 20,000 years ago.

7 Conclusion

X-ray astronomy offers insight into some of the most remarkable phenomena in Nature: the birth, evolution, and death of stars; the structure and energetics of collapsed objects, including neutron stars and black holes; the central engines in active galaxies and quasars; the distribution of so-called "dark" matter in galaxies and clusters; and the formation and evolution of structure in the early Universe.

Major advances in the investigation of these phenomena can be achieved over the next 15-20 years by implementing a balanced program in X-ray astronomy that provides for small, moderate, and large-scale missions, together with associated support programs and adequate data analysis. The concurrent development of technology is also required to ensure the vitality of the field and to encourage the strong participation of the next generation of scientists.

The plan developed by the Working Group is responsive to this need for balance. It entails a modest increase in funding for X-ray astronomy, primarily to support the initiation of an "Observer" mission series, active participation in the Explorer program, and a strengthening of the research and technology base. The Working Group believes that the plan will ensure the leadership of the United States in X-ray astronomy. It will also provide the technological basis for exploiting the scientific results that will come about in the decade of the 1990s and will allow NASA to prepare for a continuing strong scientific program in the 21st century.

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Appendices

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B. ACRONYMS AND ABBREVIATIONS

ACIS: AXAF CCD Imaging Spectrometer
ADP: Astrophysics Data Program
ADS: Astrophysics Data System
AGN: Active galactic nuclei
AIM: Astrometric Interferometry Mission
ALEXIS: Array of Low-Energy X-Ray Imaging Sensors
ANS: Astronomische Nederlandse Satelliet
AO: Announcement of Opportunity
ASCA: Advanced Satellite for Cosmology and Astrophysics
AS&E: American Science and Engineering

B. ACRONYMS AND ABBREVIATIONS *(continued)*

ASM: All Sky Monitor
AstroSPAS: German space platform for astrophysics
ATD: Advanced Technology Development
ATP: Astrophysics Theory Program
AXAF: Advanced X-Ray Astrophysics Facility
AXAF-I: AXAF-Imaging
BBXRT: Broad Band X-Ray Telescope
CCD: Charge-coupled device
COBE: Cosmic Background Explorer
CXRB: Cosmic X-ray background
DXS: Diffuse X-Ray Spectrometer
ELV: Expendable launch vehicle
ESA: European Space Agency
ESRO: European Space Research Organization
EUVE: Extreme Ultraviolet Explorer
EXOSAT: ESA X-Ray Observatory Satellite
FUSE: Far Ultraviolet Spectroscopic Explorer
GO: Guest Observer
GTO: Guaranteed Time Observer
HEAO: High Energy Astronomical Observatory
HEASARC: High Energy Astrophysics Science Archive Research Center
HEO: High Earth orbit
HETE: High Energy Transient Experiment
HEXTE: High Energy X-Ray Timing Experiment
HRC: High Resolution Camera
HRI: High Resolution Imager
HST: Hubble Space Telescope
HXIF: Hard X-Ray Imaging Facility
IRAS: Infrared Astronomical Satellite
ISM: Interstellar medium
IUE: International Ultraviolet Explorer
LAMAR: Large Area Modular Array of Reflectors
LEO: Low Earth orbit
LTSA: Long-Term Space Astrophysics
MCP: Microchannel plate
MIDEX: Middle-Range Explorer
MO&DA: Mission Operations and Data Analysis
MOXE: All-Sky X-Ray Monitor
NASA: National Aeronautics and Space Administration

B. ACRONYMS AND ABBREVIATIONS (concluded)

NIXT: Normal Incidence X-Ray Telescope
NRL: Naval Research Laboratory
OACT: Office of Advanced Concepts and Technology
OAO: Orbiting Astronomical Observatory
OSO: Orbiting Solar Observatory
OSS: Office of Space Science
PCA: Proportional Counter Array
R&A: Research and Analysis
ROSAT: Roentgen Satellite
SAC-B: Satelite de Aplicaciones Cientificas-B
SAS: Small Astronomy Satellite
SMEX: Small Explorer
SNR: Supernova remnant
SpectroSPAS: AstroSPAS platform for X-ray Spectroscopy
SQUID: Superconducting quantum interference device
SR&T: Supporting Research and Technology
SXRP: Stellar X-Ray Polarimeter
UNEX: University Explorer
VHTF: Very High Throughput Facility
VLBA: Very Long Baseline Array
XMM: X-Ray Multimirror Mission
XRS: X-Ray Spectrometer
XTE: X-Ray Timing Explorer

C. REFERENCES

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